R&D competition versus R&D cooperation in oligopolistic markets with evolving structure

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A R T I C L E   I N F O

Article history:
Received 5 March 2013
Received in revised form 25 July 2013
Accepted 17 September 2013
Available online 16 October 2013

JEL classification:
C73
L13
O33

Keywords:
R&D
Competition
Cooperation
Product innovation
Capital accumulation
Differential game

A B S T R A C T

This paper considers investment behavior of duopolistic firms subject to technological progress. It is assumed that initially both firms offer a homogeneous product, but after a stochastic waiting time they are able to implement a product innovation. Production capacities of both firms are product specific. It is shown that firms anticipate a future product innovation by under-investing (if the new product is a substitute to the established product) and higher profits, and over-investing (in case of complements) and lower profits, compared to the corresponding standard capital accumulation game. This anticipation effect is stronger in the case of R&D cooperation. Furthermore, since due to R&D cooperation firms introduce the new product at the same time, this leads to intensified competition and lower firm profits right after the new product has been introduced. In addition, we show that under R&D competition the firm that innovates first, overshoots in new-product capacity buildup in order to exploit its temporary monopoly position. Taking into account all these effects, the result is that, if the new product is neither a close substitute nor a strong complement of the established product, positive synergy effects in R&D cooperation are necessary to make it more profitable for firms than R&D competition.

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1. Introduction

In many industries R&D cooperation is a pervasive phenomenon (see e.g. Hagedoorn (2002) and Reijakkers and Hagedoorn (2006)). A key challenge incumbent firms face is whether new product developments, which open new additional submarkets that influence the demand of established products, should be carried out jointly with competitors on the market. Examples for such R&D cooperations include the Global Hybrid Cooperation between GM, Daimler, Chrysler, and BMW for the development of hybrid cars, the cooperation between Sony and Samsung for the development of TFT-LCD screens, or the cooperation between Lenovo and NEC to develop tablet computers.1 On the other hand, several of the innovations opening new submarkets were introduced by incumbents who did not engage in R&D cooperation, like the introduction of MP3 players by Apple. An important difference between the case of MP3 players and previous examples is that MP3 players are complements to the established product (PCs) rather than substitutes. Furthermore, the degree of differentiation between the two products in the MP3 example seems to be larger than in the previous three examples, so that the linkage between the two markets seems weaker.

1 It should be noted that in all three examples the new products are substitutes to the existing ones. To illustrate, one of the main producers on the PC and tablet market, Samsung Electronics, stated that it expects the global personal computer market to shrink by 5% in 2013 as consumer demand continues to shift to mobile devices such as tablet computers (see India Times (2013; http://www.indiatimes.com/pc-and-laptop/samsung-global-pc-sales-to-reduce-by-5_-57356.html)).
Based on these observations, the paper addresses the following research questions:

• Under which circumstances do incumbents have incentives to cooperate in the new product development?
• How are the investment patterns before and after the emergence of the new sub-market influenced by cooperation/non-cooperation in the innovation project?

In the literature the issue of R&D cooperation has attracted substantial interest. Influential theoretical contributions include D’Aspremont and Jacquemin (1988), Choi (1993), and Goyal and Joshi (2003). The large literature based on these papers relies on static models, but in order to capture the main implications of R&D cooperations in industry settings like the ones discussed above, a dynamic framework is needed. In particular, firms’ investment incentives are influenced by the expected future introduction of new products. Furthermore, the induced changes in investment patterns of competitors influence also the current profitability of investments in the established product. However, the few dynamic analyses of R&D cooperation (see Martin (2002), Miyagiwa and Ohno (2002), Erkal and Piccinn (2010), Cellini and Lambertini (2009)) do not study interdependencies with existing products. Also, all these contributions focus on R&D cooperation with respect to process innovation.

This paper addresses several issues that are not covered in the literature so far. First, we explicitly model the effects of R&D cooperation on the behavior of firms on established markets. This allows us to examine how the linkage between the established and the new product affects incentives for R&D cooperation. Second, we explicitly study how the behavior of incumbents with respect to the established product is influenced by future new product introductions. To capture the resulting anticipation effect we focus on capacity dynamics, thereby contributing to the literature on dynamic oligopolistic competition (e.g. Jun and Vives (2004), Besanko and Doraszelski (2004), Besanko et al. (2010a,b)). Third, in a dynamic setting we explicitly take into account that R&D cooperation for product innovation has a synchronizing effect on product introduction dates across competitors. Fourth, in addition to the pure knowledge sharing aspect, which leads to the synchronization effect, we also model potential synergies generated by R&D cooperations (see e.g. Link et al. (1996) or Link (1998) for empirical evidence for the existence of synergies in R&D cooperations). This feature of the model allows us to understand under which circumstances positive synergy effects are necessary to give firms an incentive to cooperate in R&D.

We consider a dynamic oligopoly model, where incumbent firms offer an established homogeneous product. At some ex-ante unknown point in time the range of products is enlarged, because one or several of the competing firms obtain the option to introduce a new product, which is vertically and horizontally differentiated from the existing product. Capacities cannot be (fully) transferred between the production of different products. Therefore, the introduction of the new product reduces (in case of substitutes) or increases (in case of complements) the value of the existing capacities. The firms’ objectives are to maximize their total discounted profits by optimally selecting their investments in production capacities for the different products they offer. Firms can enter an R&D cooperation with the competitor in order to develop the new product. Entering such a cooperation reduces the expected time until the firm can introduce the new product because the firm gets access to the R&D results of the partner and the cooperation might also generate synergies in the R&D activities. The drawback of such a cooperation is that the partner will be able to introduce the new product at the same time, thereby intensifying market competition.

The developed model has the form of a piecewise deterministic differential game with different modes. In the initial mode none of the firms has introduced the new product. An introduction of a new product results in a switch to a new mode opening a broader range of investment possibilities for the innovating firm.

The characterization of Markov Perfect Equilibria (MPE) of the game leads to the following answers to our research questions. Although the model abstracts from explicit cooperation costs and knowledge spillover considerations, R&D cooperation has implicit costs due to strategic interactions on the market. We identify two main effects responsible for these costs: i) R&D cooperation implies that after a successful innovation, the new product is available for market introduction to all cooperation partners. Hence, competition in the new submarket emerges immediately after the introduction of the new product (we denote this as the synchronization effect). ii) In case the new product is a complement to the established one, the anticipation of the eventual introduction of the new product induces an increase in investment in capacities of the established product already prior to the new product introduction. The increased investment brings the price for the established product closer to the competitive level, thereby reducing firm profits. This anticipation effect is stronger if firms cooperate in R&D, since the expected innovation time is shorter. This results in additional implicit costs of R&D cooperation.

If the new product is neither a close substitute nor a strong complement of the established product, in the absence of synergies from R&D cooperation the overall implicit costs outweigh the gains of cooperation. These gains consist not only of reduction of expected innovation time, but also of a reduction in capacity adjustment costs for the new product (adjustment cost effect). We show that under R&D competition the (intertemporal optimal) capacity trajectory of the innovator is non-monotonic. Directly after the new product introduction, the innovator builds up the corresponding capacity to exploit the temporary monopoly position. After the competitor has also introduced the new product, the innovator scraps parts of this installed capacity to keep product prices at a sufficiently high level. The costs associated with such ‘overshooting’ of capacity build-up are avoided in case of R&D cooperation, because there we observe monotone capacity adjustments on both markets after the innovation.

Another main insight from our dynamic analysis is that the anticipation of the market introduction of a substitute to the established product acts as a collusion device. If firms expect that a substitute for their current product will be introduced, the expected return from current capacity investment decreases. Hence, such expectations lead to lower capacities and a higher price for the established product. This moves the price closer to the monopoly price and increases current total industry profits compared to a situation without such an anticipation.

The paper is organized as follows. The next section presents the model. This is followed by a characterization of the Markov Perfect Equilibria of the game in Section 3. Section 4 discusses the economic implications of our analysis and Section 5 concludes.

2. The model

We consider a duopoly where both firms, denoted Firm A and Firm B, have initial capacities $k_A(0) = AB$ available for production of an established product, denoted as product 1. At $t = 0$ both firms start an innovation project aiming at the development of a new differentiated product (product 2). The completion time of the innovation project of firm $f$ is denoted by $t_f = AB$. The project might be carried out independently or jointly. In the case of independent R&D, which we
will refer to as R&D competition, both firms in general have different project completion times. The new product becomes available only to the firm which has finished its project at that time. Completion times are exponentially distributed with arrival rate $\lambda^\text{comp} > 0$ and independent across firms. In order to focus the analysis on the capacity dynamics of both firms, the distribution of the project completion times is assumed to be exogenous.

Alternatively, in the case of R&D cooperation, the firms engage in a joint innovation project, whose completion time $T^\text{coop}$ is exponentially distributed with arrival rate $\lambda^\text{comp} > 0$. At this completion time, the new product becomes available for both firms to produce. Since in the R&D competition case the minimal completion time $\min\{T^\text{A}, T^\text{B}\}$ is exponentially distributed with arrival rate $2\lambda^\text{comp}$, we assume $\lambda^\text{comp} > 0$ as the degree of synergies that arise due to cooperation of the two firms.

In order to be able to produce positive quantities of this new product, the firms have to build up production capacities, where initial capacities are $K_i^0(0) = 0$, $i = A, B$. At the same time they can adjust their capacities for the established product. Production capacities here involve physical capital at production facilities as well as the specific know-how, supply chains, and distribution channels. Production capacities are specific to the production of either the established or the new product.\textsuperscript{5}

It is assumed that both firms at each point in time fully exploit their production capacities.\textsuperscript{6} Prices are given by the linear inverse demand system

\begin{align}
 p_1(t) &= 1 - (K_{1A}(t) + K_{1B}(t)) - \eta(K_{2A}(t) + K_{2B}(t)), \\
p_2(t) &= 1 + \theta - \eta(K_{1A}(t) + K_{1B}(t)) - (K_{2A}(t) + K_{2B}(t)).
\end{align}

This type of inverse demand system can be derived from a representative consumer model with a quality-augmented version of the standard quadratic utility function (see Symeonidis (2003), Vives (1999)). The parameter $\eta$ determines the degree of horizontal differentiation, where $-1 < \eta < 1$. The parameter $\theta > 0$ measures the degree of vertical differentiation between the two products, where it is assumed that the new product is of higher or equal quality. We assume that production costs are linear, and for reasons of simplicity we assume that marginal production costs for both products are normalized to zero.

Investment costs are assumed to be linear--quadratic and symmetric across firms, i.e., $\begin{aligned} C_i(L_i(t)) &= b_i L_i(t) + \frac{c_i L_i(t)^2}{2}, \end{aligned}$ where $L_i(t)$ denotes the investment of firm $f \in \{A, B\}$ for product $i = 1, 2$ at time $t$. The parameter $b_i > 0$ is the unit price of capacity for product $i$ and $c_i > 0$ is the adjustment cost parameter. We allow for disinvestment of firms and hence $L_i(t)$ may be any real number for any $t$ taking into account the non-negativity of the capacities. Investments (or disinvestments) in capacities to produce the new product are only possible at $t$ if the new product has become available at some $\tau \leq t$. To capture this constraint formally we define four modes of the game (see Dockner et al. (2000), Chapter 8 for a general description of multi-mode differential games referred to as 'Piecewise deterministic games'). The first mode, labeled as $m_1$, corresponds to the periods where the new product has not become available yet. In the modes $m_2$ and $m_3$ the new product is available only to one of the two firms, where in mode $m_2$ firm $A$ innovates first, whereas firm $B$ is the innovation leader in mode $m_3$. One of these two modes always occurs under R&D competition in the time interval between $\min\{T^\text{A}, T^\text{B}\}$ and $\max\{T^\text{A}, T^\text{B}\}$. Under R&D cooperation none of these modes can occur. Instead, with R&D cooperation there is a direct transition from mode $m_1$ to mode $m_4$ where both firms have access to the new product. Also under R&D cooperation, mode $m_4$ is eventually reached after the second firm has completed its innovation project. See Fig. 1 for a graphical summary of these transitions.

In mathematical terms we define a Markov process $m(t)$ on the set $\mathcal{M} := \{m_1, m_2, m_3, m_4\}$ with $m(0) = m_1$, and the transition rates given in Fig. 1. The restrictions on investment are then captured by the constraints

\begin{align}
 L_{1f}(t) &= 0 \quad \forall t \text{ s.t. } m(t) = m_1, f = A, B, \\
 L_{2f}(t) &= 0 \quad \forall t \text{ s.t. } m(t) = m_2, \\
 L_{1f}(t) &= 0 \quad \forall t \text{ s.t. } m(t) = m_3,
\end{align}

which have to be non-negative and are bounded above by some (large) value $\bar{R}_{if}$, $i = 1, 2$, $f = A, B$. For simplicity no depreciation of capital is considered.

Each of the two firms chooses its investments in order to maximize its discounted profits net of investment costs over an infinite horizon. Denoting by $r > 0$ the discount rate, the objective functions of the two firms are given by

\begin{align}
 J_f &= \mathbb{E} \left[ \int_0^\infty e^{-rt} \left[ 1 - (K_{1A} + K_{1B}) - \eta(K_{2A} + K_{2B}) \right] K_{1f} + (1 + \theta - \eta(K_{1A} + K_{1B}) - (K_{2A} + K_{2B})) K_{2f} - b_1 L_{1f} - \frac{c_1 L_{1f}^2}{2} - b_2 L_{2f} - \frac{c_2 L_{2f}^2}{2} \right] dt, \quad \text{(6)}
\end{align}

subject to (3), (4), (5), where the expectation is taken with respect to the stochastic process $m(t)$.

We assume that firms use stationary Markovian feedback strategies and focus on behavior under a Markov Perfect Equilibrium (MPE). Since the precise definition of such an equilibrium in our multi-mode concept is not completely standard we provide an exact definition of an MPE in the Appendix A. We rely in our analysis on the concept of a Markov-Perfect Equilibrium rather than on alternatives like Open-Loop Nash Equilibria (OLNE) because we believe that the level of commitment of firms assumed under OLNE (each firm has to commit at time $t = 0$ to its investment pattern for the entire infinite time horizon) is not appropriate for the problem under consideration here.
3. Characterization of the Markov perfect equilibria

We characterize the Markov-perfect equilibrium of the described dynamic capacity game using a multi-modal approach. As pointed out in Dockner et al. (2000), for multi-modal games the value functions of the players depend not only on the states, but also on the mode of the game. Formally, the value function of firm $f = A$ is a mapping $V_f : [0, K_1] \times [0, K_2] \times M \to \mathbb{R}$, where in mode $m_1$ the value functions only have to be determined on the subset of the state space where $K_{2A} = K_{2B} = 0$ and in mode $m_2$ ($m_3$) only on the subset where $K_{2B} = 0$ ($K_{2A} = 0$). The Hamilton-Jacobi-Bellman (HJB) equations differ between modes. In particular in mode $m_1$ we have under R&D competition

$$r V_f(K_{1f}, 0, K_{1g}, 0, m_1) = \max_{i_f} \left[ \left( 1 - (K_{1A} + K_{1B}) \right) K_{1f} - b_i l_{1f} - \frac{\zeta}{2} l^2_{1f} \right] + \frac{\partial V_f(\cdot, m_1)}{\partial K_{1f}} l_{1f} + \lambda_{\text{comp}} \left( V_f(\cdot, m_2) - V_f(\cdot, m_1) \right), \quad \tag{7}$$

$$f, g = A, B, g \neq f.$$

Intuitively, the expression in the square brackets on the first line of the right hand side stands for the instantaneous profit of producing the established product. The next two terms capture the effects of changes of the capacities of the established product of firm $f$ and its competitor. The last two terms deal with the value function effects of the appearance of the new product on the market (i.e. the potential jumps from mode $m_1$ to mode $m_2$ or mode $m_3$). For R&D cooperation we obtain

$$r V_f(K_{1f}, 0, K_{1g}, 0, m_1) = \max_{i_f} \left[ \left( 1 - (K_{1A} + K_{1B}) \right) K_{1f} - b_i l_{1f} - \frac{\zeta}{2} l^2_{1f} \right] + \frac{\partial V_f(\cdot, m_1)}{\partial K_{1f}} l_{1f} + \lambda_{\text{comp}} \left( V_f(\cdot, m_2) - V_f(\cdot, m_1) \right), \quad \tag{8}$$

$$f, g = A, B, g \neq f.$$

The HJB equation is similar to (8) with the exception that in case the new product arrives it is simultaneously adopted by both firms (i.e. the mode jumps from $m_1$ to $m_4$). In mode $m_2$ we have for the innovator firm $A$

$$r V_f(K_{1A}, K_{2A}, K_{1B}, 0, m_2) = \max_{i_A} \left[ \left( 1 - (K_{1A} + K_{1B}) \right) K_{1A} - b_i l_{1A} - \frac{\zeta}{2} l^2_{1A} \right] + \frac{\partial V_f(\cdot, m_1)}{\partial K_{1A}} l_{1A} + \lambda_{\text{comp}} \left( V_f(\cdot, m_4) - V_f(\cdot, m_3) \right), \quad \tag{9}$$

The instantaneous profit of firm $A$ is given on the first two lines of the right hand side, where firm $A$ now also receives profits from the new market. There are three relevant capital stocks whose dynamics has to be taken into account by firm $A$. The final term on the right hand side captures the value function effect of firm $B$ becoming active on the new product market (i.e. jump from $m_2$ to $m_4$) at a yet unknown future point in time. For the laggard firm $B$ we obtain

$$r V_g(K_{1A}, K_{2B}, 0, m_4) = \max_{i_g} \left[ \left( 1 - (K_{1A} + K_{1B}) \right) K_{1A} - b_i l_{1A} - \frac{\zeta}{2} l^2_{1A} \right] + \frac{\partial V_f(\cdot, m_2)}{\partial K_{1A}} l_{1A} + \lambda_{\text{comp}} \left( V_f(\cdot, m_4) - V_f(\cdot, m_3) \right), \quad \tag{10}$$

The only difference to Eq. (9) is that firm $B$ does not make any profits yet with the new product. Symmetric equations arise in mode $m_3$, where firm $B$ is the innovator and firm $A$ is the laggard. Finally, in mode $m_4$ the HJB-equation reads

$$r V_f(K_{1A}, K_{2A}, K_{1B}, K_{2B}, m_4) = \max_{i_A} \left[ \left( 1 - (K_{1A} + K_{1B}) \right) K_{1A} - b_i l_{1A} - \frac{\zeta}{2} l^2_{1A} \right] + \frac{\partial V_f(\cdot, m_3)}{\partial K_{1A}} l_{1A} + \lambda_{\text{comp}} \left( V_f(\cdot, m_4) - V_f(\cdot, m_3) \right), \quad \tag{11}$$

This is a standard HJB for a capital accumulation game where each firm produces two products. Considering the first order conditions, it follows directly from these equations that the equilibrium investment strategies are of the form

$$I^n_f(K, m_i) = \frac{1}{\epsilon} \left( \frac{\partial V_f(K, m_i)}{\partial K_{1f}} - b_i \right) \quad i = 1, 2, \quad f, g = A, B, m \in M,$$

with $K = (K_{1A}, K_{2A}, K_{1B}, K_{2B})$. Since the game is symmetric with respect to the two firms, we will concentrate on the characterization of symmetric Markov-perfect equilibria. Due to the linear quadratic structure of the game the following form for the value functions can be assumed:

$$V_f(K, m_4) = \alpha^4 + \beta^2 K_{1f} + \chi^2 K_{1g} + \phi K_{2f} + \psi K_{2g} + \gamma K_{1f}^2 + \phi K_{2f}^2 + \psi K_{2g}^2 + \gamma K_{1g}^2 + \epsilon K_{2f}^2 + \sigma K_{1f} K_{1g} + \sigma K_{2f} K_{2g} + \sigma K_{1f} K_{2g} + \sigma K_{1g} K_{2f}, \quad \tag{12}$$

$$V_A(K_{1A}, K_{2A}, K_{1B}, 0, m_2) = \alpha_2^4 + \beta_2^2 K_{1A} + \chi_2^2 K_{1B} + \phi_2 K_{2A} + \psi_2 K_{2B} + \gamma_2 K_{1A}^2 + \phi_2 K_{2A}^2 + \psi_2 K_{2B}^2 + \gamma_2 K_{1B}^2 + \epsilon_2 K_{2A}^2 + \sigma_2 K_{1A} K_{1B} + \sigma_2 K_{2A} K_{2B} + \sigma_2 K_{1A} K_{2B} + \sigma_2 K_{2A} K_{1B}, \quad \tag{13}$$

$$V_A(K_{1A}, K_{2A}, K_{1B}, 0, m_3) = \alpha_4^4 + \beta_4^2 K_{1A} + \chi_4^2 K_{1B} + \phi_4 K_{2A} + \psi_4 K_{2B} + \gamma_4 K_{1A}^2 + \phi_4 K_{2A}^2 + \psi_4 K_{2B}^2 + \gamma_4 K_{1B}^2 + \epsilon_4 K_{2A}^2 + \sigma_4 K_{1A} K_{1B} + \sigma_4 K_{2A} K_{2B} + \sigma_4 K_{1A} K_{2B} + \sigma_4 K_{2A} K_{1B}, \quad \tag{14}$$

$$V_A(K_{1A}, K_{2A}, 0, 0, m_4) = \alpha_4^4 + \beta_4 K_{1A} + \chi_4 K_{1B} + \phi_4 K_{2A} + \psi_4 K_{2B} + \gamma_4 K_{1A}^2 + \phi_4 K_{2A}^2 + \psi_4 K_{2B}^2 + \gamma_4 K_{1B}^2 + \epsilon_4 K_{2A}^2 + \sigma_4 K_{1A} K_{1B} + \sigma_4 K_{2A} K_{2B} + \sigma_4 K_{1A} K_{2B} + \sigma_4 K_{2A} K_{1B}, \quad \tag{15}$$

with $f, g = A, B, f \neq g$. The value functions in mode $m_3$ are completely symmetric to those in mode $m_2$ with reversed firm roles and $\alpha_2 = \alpha_4$, $\beta_2^2 = \beta_4^2$, ... for $g = A, B, f \neq g$.

In order to determine the coefficients of these value functions we follow a standard approach by inserting the equilibrium investment rules and the quadratic value functions for the different modes into the HJB-equations. In particular, for the case of R&D competition the value functions for all four modes are inserted into (7) and (9)–(11), whereas for the case of R&D cooperation the value functions for modes $m_1$ and $m_4$ are inserted into (8) and (11). Comparing the coefficients of the capital stock terms of different degrees yields 41 nonlinear equations in 41 unknowns under R&D competition and 21 nonlinear equations in 21 unknowns under R&D cooperation. Solving these systems is facilitated by the fact that they can be solved recursively, starting with mode $m_4$ and then proceeding to modes $m_2$ and $m_1$. In all results to be presented below it has been checked that (globally) stable steady states exist in all modes, which implies that transversality conditions are satisfied.
4. Economic analysis

In what follows we address the economic questions posed in the Introduction by carrying out a numerical analysis. We depart from the following default set of parameters

\[ \lambda^{\text{comp}} = 0.05, \lambda^{\text{coop}} = 0.1, \theta = 0, b_1 = b_2 = 0, c = 5, r = 0.04, \]

where we will present robustness checks of the qualitative findings with respect to variations of these parameters at the end of the section and in Appendix B. Without loss of generality we always assume that the price of capital is normalized to zero, i.e. \( b_1 = 0 \). In the default setting we have \( \lambda^{\text{comp}} = 2\lambda^{\text{coop}} \), which means that we consider a scenario without R&D synergies. Results differ qualitatively between the cases where the new product is a substitute or a complement to the established product. Hence, we always separately discuss results for cases where the new product is a substitute or a complement to the established product.

In all the analyses, the initial levels of the capital stocks of the established product are set to the steady state levels arising in the Markov-perfect equilibrium of the standard capital accumulation game where both firms produce only the established product forever. In some of our discussion below we will refer to this capacity level as the no-innovation benchmark. Setting such initial conditions can be interpreted in a way that before the start of the R&D project(s) firms ignored the possibility of new products being introduced into the market.

4.1. Incentives for R&D cooperation

To examine the incentives of firms to engage in R&D cooperation, Fig. 2 considers the relative difference of the value functions of the firms under R&D competition and under R&D cooperation evaluated at the initial capital stocks. It can be clearly seen that in the absence of synergies there is no incentive to cooperate for almost all values of the horizontal differentiation parameter \( \eta \). This is quite remarkable given that we do not assume that cooperation induces any explicit costs for the firms. Furthermore, it can be seen that the relative advantage of R&D cooperation crucially depends on the degree of horizontal differentiation. In particular, for a large part of the \( \eta \)-interval \((-1,1)\) R&D cooperation is more attractive the smaller the horizontal differentiation parameter \( \eta \) is. Although certainly many factors not captured in our model also influence actual cooperation decisions of firms, still this finding is qualitatively consistent with the examples discussed in the Introduction. In particular, in the three examples where the new product is a substitute to the established one (hybrid engines, TFT-LCD screens, tablet PCs), R&D cooperations occur. However, no cooperation is observed in the MP3–PC example, where the relationship between the products is complementary.

To better understand the factors driving cooperation incentives, three effects have to be considered:

(i) Anticipation effect,
(ii) Synchronization effect,
(iii) Adjustment cost effect.

Below we discuss each of these effects in detail.

4.1.1. Anticipation effect

To explain the anticipation effect, the dynamics of production capacities for the established product prior to the introduction of the new product has to be considered. Fig. 3 shows the dynamics of production capacities for the old product and instantaneous profits of the firms in the periods before the new product is introduced (i.e. during mode \( m_1 \)). It can be seen that starting the R&D projects influences the capacity levels for the established product even before the new product is introduced. In particular, both under R&D cooperation and R&D competition the firm invests less if the anticipated new product is a substitute. The reason is that the firm takes into account that after the introduction of the new product the revenue generated by one unit of capital stock of the established product will decrease. This reduces the value of the capital stock already before the new product arrives. Hence, the firms invest less in mode \( m_1 \) compared to the no-innovation benchmark. Due to this underinvestment the price of the established product moves closer to the monopoly price and the instantaneous payoffs of both firms go up compared to the no-innovation benchmark.

![Fig. 2](image-url) The relative difference in game values between R&D competition and R&D cooperation when no synergies from cooperation are present.

![Fig. 3](image-url) Dynamics of (a) capital stocks and (b) instantaneous profits in mode \( m_1 \) under R&D cooperation (blue) and R&D competition (purple) for \( \eta = 0.5 \) (solid) and \( \eta = -0.5 \) (dashed). The horizontal black line refers to the no-innovation benchmark. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
If the new product is a complement to the established product, its anticipated introduction has a positive effect on the value of the established product’s capital stock. Therefore, firms invest more (prior to the new product introduction) compared to the no-innovation benchmark. This leads to lower prices and lower instantaneous payoffs.

Comparing the dynamics under R&D competition and R&D cooperation we see that the size of the anticipation effect in mode \( m_1 \) is larger under R&D cooperation than under competition. The reason is that under R&D cooperation the change of the value of the established product’s capital stock due to the anticipated innovation is larger. In the case of substitutes we get a larger reduction in the value for the following two reasons. First, under R&D cooperation both firms introduce the new product at \( \tau^{coop} \). This implies a stronger price decrease for the established product compared to R&D competition. In the latter case only one firm introduces the new product at the time when the new product first reaches the market. Second, under R&D cooperation for each firm the expected time until it introduces the new product is lower than under competition. Once the firm offers both products, the value of the established product’s capital stock further decreases due to a cannibalization effect. Analogous arguments show that in the case of complements the overinvestment is larger under R&D cooperation because the value of the established product’s capital stock increases more under R&D cooperation compared to R&D competition. It should be noted that the presence of synergies enhances the difference in the size of the anticipation effect between the cases of R&D cooperation and R&D competition, because the expected time to the new product introduction is then shorter under R&D cooperation.

For complements this results in lower payoffs under cooperation in mode \( m_2 \), whereas for substitutes it is the other way round. As can also be seen in Fig. 3, the size of the anticipation effect and of the resulting difference between R&D cooperation and competition is larger for complements than for substitutes.

### 4.1.2. Synchronization effect

An important implication of R&D cooperation is that the introduction of the new product is synchronized among the two firms. We refer to this as the synchronization effect. It implies that immediately after the innovation there is duopolistic competition also on the market for the new product. Under R&D competition there is always a time interval where only one firm is active on the new market. During this interval the innovator is gaining a relatively high payoff due to its temporary monopoly position with respect to the new product. The laggard, however, is worse off than it would be in a situation where both firms introduce the new product simultaneously. Ex-ante firms do not know which will be the first innovator. However, the expected market profit (net of capital adjustment costs) under R&D competition in the time interval between the two innovation times is higher than in the duopolistic scenario under R&D cooperation. This is an implication of the fact that industry profits are larger under monopoly than under duopoly. Fig. 4 illustrates this observation. It compares the average instantaneous payoff of a firm in the steady states of modes \( m_2 \) and \( m_1 \) with its payoff in the steady state of mode \( m_4 \). It should be noted that in the steady state no capacity investments occur, which means that investment costs are irrelevant. It can be clearly seen that in the considered range of the degree of horizontal differentiation indeed the average payoff in the steady states of the asymmetric modes under R&D competition is larger than the steady state payoff in mode \( m_4 \), where both firms offer the new product. Furthermore, the relative difference increases as \( \eta \) becomes smaller.

#### 4.1.3. Adjustment cost effect

The adjustment cost effect arises from the difference in the capital adjustment patterns between the two R&D scenarios. Figs. 5 and 6 show the equilibrium dynamics of the four capital stocks with R&D competition and R&D cooperation, respectively, under the assumptions that innovations occur exactly at their expected time. In case of R&D competition we assume that firm A is the first innovator.

Focusing first on the case where the two products are substitutes it can be seen that under R&D competition the innovator reduces investment in the established product after the new product is introduced. Also the innovation laggard does so directly after the introduction of the new product. This is caused by the increased competition on the market, since the introduction of the new product reduces the price of the established product for a given quantity. The innovator has an additional incentive to reduce quantities of the established product, because this increases the price of the new product. Once the new product is also introduced by firm B \((\tau_2 = \tau)\), capital stocks quickly converge to the symmetric steady state. Due to the absence of vertical differentiation \((\theta = 0)\) the steady state levels of both products coincide. It should be noted that the dynamics of the capital stocks of firm A have a non-monotonic pattern. During the period where this firm is the only producer of the new product \((\tau_2 < t < \tau)\), it increases its capacity for the new product and decreases that of the established product. After the introduction of the new product by firm B, exactly the opposite dynamics arise. Firm A reduces \( K_2 \) and increases \( K_1 \). This is a reaction to i) the increase in new product capacity of its competitor, which reduces the price of the new product, and ii) the decrease of \( K_1 \), which provides incentives for firm A to expand capacity on the established market. In this way the sequential introduction of the new product by the two firms creates an overshooting pattern of production capacities of firm A.

Comparing this overshooting pattern with the capacity dynamics under R&D cooperation (see Fig. 5(b)) we observe that, contrary to the case of R&D competition, under cooperation there is no overshooting of capacities and all capital stocks approach the long run steady state in a monotic way. Consequently, total capital adjustment costs are smaller under R&D cooperation.

In the case of complements, the introduction of the new product triggers an increase in the capacity investments of the established product. This is because the introduction of the new product creates additional demand for the established product. The symmetric steady state reached after the introduction of the new product by firm B in this case induces a larger capacity for the established product than in the no-innovation benchmark. Like in the case of substitutes, under R&D competition overshooting occurs with respect to the capital stocks of the innovator firm A. In the complements case the capacities for both products increase between \( \tau_a \) and \( \tau_b \) and then decrease after the introduction of the new product by firm B. Under R&D cooperation no

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7. It should be noted that the observed overshooting effect is not an implication of our assumption that firms always produce up to capacity. Actually, the overshooting effect with respect to output would be even stronger if we drop this assumption, because in such a scenario firm A could reduce quantities without incurring additional adjustment costs after the new product has been introduced by firm B.
such overshooting occurs. For this reason also if the new product is complementary to the established one, expected capital adjustment costs are larger in the R&D competition case.

4.1.4. Adding up the effects

Considering Fig. 2 we conclude that the synchronization effect (plus the anticipation effect in case of complements), which favors R&D competition, is dominant. Avoiding synchronization of the time of the introduction of the new product enhances expected market profits to a sufficient degree so that the extra adjustment costs are more than compensated. Consequently, firms should decide for R&D competition in the absence of synergies.

4.2. Impact of R&D synergies

In the discussion so far it was assumed that R&D cooperation does not generate any synergies in the sense that the expected time until the new product can be first introduced to the market is the same under R&D cooperation and R&D competition. As mentioned in the Introduction, empirical work suggests that cooperation between different firms in the market might lead to synergies in the R&D activities of these firms. In our model positive synergies are captured by assuming that \( \lambda_{\text{comp}} > 2 \lambda_{\text{comp}} \) holds. In the case of such positive synergies, a fourth effect is added to the three effects just discussed. Under synergies the expected time span until the first introduction of the new product is shorter under R&D cooperation and hence firms expect the corresponding increase in their instantaneous payoffs to occur earlier. This makes R&D cooperation more attractive. We refer to this effect as the synergy effect.

To explore this issue more deeply, we define by \( \lambda^* \) the minimal value of the innovation arrival rate such that the firms' value functions under R&D cooperation exceed that of R&D competition for all \( \lambda_{\text{comp}} \geq \lambda^* \). In Fig. 7 this threshold value is depicted for varying degrees of horizontal differentiation and compared to the value \( 2 \lambda_{\text{comp}} \) corresponding to no synergies. Consistent with our discussion above, we observe that for all values of \( \eta \) apart from the extreme degrees of differentiation positive synergies are needed to make R&D cooperation attractive. Since the payoff increase resulting from the introduction of the new product is larger for complements than for substitutes, the synergy effect is more pronounced for negative values of \( \eta \). Hence, as confirmed in the figure, particularly high synergies are needed if the two products are (not too strong) substitutes. The reason that only weak synergies are needed to make R&D cooperation attractive in the case of close substitutes is that in such a scenario the synchronization effect becomes very small. The sole producer of the new product has

\[ \lambda_{\text{comp}} \geq \lambda^* \]

Fig. 7. The threshold value \( \lambda^* \) for varying degree of horizontal differentiation.
very little market power because the new product is almost homogeneous to the established one. The relatively low values of $\lambda^*$ for values of $\eta$ close to $-1$ are due to the strength of the adjustment cost effect in the case of strong complements.

4.3. Robustness

Our discussion of the different qualitative effects resulting from the choice between R&D cooperation and R&D competition has been based on a particular parameter constellation. It is important to check robustness of the qualitative statements with respect to variations of the key parameters of the model. Such a sensitivity check has been carried out and to illustrate the robustness of our results we depict in Fig. 8 the changes in the $\lambda^*$ curve if the discount rate, the capital adjustment cost parameter and the degree of vertical differentiation is varied. A more extensive discussion of the robustness of our findings is provided in Appendix B.

It can be seen that the qualitative features of this curve, in particular the inverse U-shape and the requirement for positive synergies for almost the entire range of $\eta$ values, stay intact. The fact that higher discounting moves the curve downwards can be explained by the increased relevance of the synergy effect. The expected reduction of the arrival time of the innovation caused by an increase of the arrival rate is valued more if the discount rate is higher. Hence, a smaller adjustment costs in mode $t_1$ stems from the anticipation effect and, as discussed above, this effect is stronger under R&D cooperation than under R&D competition. If the new product is a substitute of the established one, this reasoning implies that R&D cooperation has a negative effect on (instantaneous) welfare, whereas R&D cooperation is welfare-enhancing if the new product is a complement. Considering the modes after the innovation, it is easy to see that welfare in modes $m_2$ and $m_3$, where only one firm offers both products, is smaller than in mode $m_4$, where both firms offer both products. This is due to larger total output and smaller capacity adjustment costs in mode $m_4$. Since R&D cooperation leads to a direct transition from $m_3$ to $m_4$ (instantaneous) welfare after the introduction of the new product is always larger under R&D cooperation than under R&D competition. These qualitative statements have been confirmed by numerical analysis. This analysis also shows that for the parameter settings considered above, in the case of substitutes the negative welfare effects of R&D cooperation prior to innovation is dominated

4.4. Welfare effects

To conclude our analysis we briefly consider the welfare implications of R&D cooperation. Intuition suggests that at any point in time in mode $m_1$, prior to the introduction of the new product, an increase of the total quantity of the established product, relative to the no-innovation benchmark, is welfare-enhancing. The deviation of the output from the no-innovation benchmark in $m_1$ stems from the anticipation effect and, as discussed above, this effect is stronger under R&D cooperation than under R&D competition. If the new product is a substitute of the established one, this reasoning implies that R&D cooperation has a negative effect on (instantaneous) welfare, whereas R&D cooperation is welfare-enhancing if the new product is a complement. Considering the modes after the innovation, it is easy to see that welfare in modes $m_2$ and $m_3$, where only one firm offers both products, is smaller than in mode $m_4$, where both firms offer both products. This is due to larger total output and smaller capacity adjustment costs in mode $m_4$. Since R&D cooperation leads to a direct transition from $m_3$ to $m_4$ (instantaneous) welfare after the introduction of the new product is always larger under R&D cooperation than under R&D competition. These qualitative statements have been confirmed by numerical analysis. This analysis also shows that for the parameter settings considered above, in the case of substitutes the negative welfare effects of R&D cooperation prior to innovation is dominated

\[ W = \int_0^\infty e^{-r t} \left[ U(1_1 + 1_2 + 1_3) - r_1 (1_1 + 1_3) - \frac{1}{2} \left( \delta_{11} + \delta_{13} \right) - b_1 (1_1 + 1_3) - \frac{1}{2} \left( \delta_{11} + \delta_{13} \right) - \delta_{12} (1_2 + 1_3) \right] dt, \]

where

\[ U(Q_1, Q_2) = Q_1 + (1 + \theta) Q_2 - \frac{1}{2} Q_1^2 - \frac{1}{2} Q_2^2 - \gamma Q_1 Q_2, \]

is the standard Dixit-Stiglitz utility function giving rise to a linear demand system.
by the positive effects after innovation such that also in the absence of synergies the discounted welfare stream under R&D cooperation is larger than under competition regardless of the degree of differentiation. In case of complements R&D cooperation increases welfare before and after the innovation. Therefore, also in the complements case the effect of R&D cooperation on the discounted welfare stream is clearly positive.

5. Conclusions

This paper analyzes the interplay between capacity dynamics and technological progress in an oligopolistic market. We focus on product innovation and study how anticipated and actual introduction of new products influence market dynamics. In particular, we characterize the implications of R&D cooperation in product innovation on the investment behavior of established firms in an industry. We identify three effects, which influence the relative profitability of R&D cooperation: the anticipation effect, the synchronization effect, and the adjustment cost effect. We show that the sign and the size of these effects depend on the degree of product differentiation. We find that, although R&D competition is associated with overshooting of the capacity dynamics for both products and, in case of substitutes, also leads to smaller firm profits than R&D cooperation prior to the innovation date, still firms prefer not to cooperate in R&D in the absence of sufficiently strong synergy effects. Given that R&D cooperation is preferable from a welfare perspective, these insights call for policy measures stimulating R&D cooperation.

The present paper discusses a framework where the two firms are completely symmetric. It is therefore worthwhile to discuss the implications of asymmetries, in particular, the case where one of the firms has a greater potential to innovate. In such a scenario it is expected that the incentive to cooperate is smaller for the firm with the larger arrival rate for the innovation, because it is likely that this firm will capture the temporary monopoly position when firms compete in R&D. This makes the synchronization effect stronger for that firm. An extreme case of asymmetries, where one of the incumbents has an arrival rate of zero is analyzed in Dawid et al. (2010).

In order to concentrate the analysis on capacity investment dynamics we have assumed in this paper that innovation arrival rates are exogenously given. Therefore, an important extension is to introduce knowledge stocks of the firms into the analysis, which can be increased by R&D investments, and to assume that arrival rates depend on knowledge stocks (see e.g. Doraszelski (2003)). Since such a formulation leads to a differential game which does not have a linear quadratic structure, numerical methods like collocation will have to be employed in such an analysis. An important issue that can be addressed in such a setting is the impact of market share on the established market on the incentives to invest in product innovation.

Finally, it would be interesting to analyze the impact of the number of firms being active in the established market. In such a context the implications of different types of R&D networks on firm profitability could be analyzed under the assumption that firms follow Markov-perfect equilibrium behavior. We leave this as an interesting topic for future research.

Appendix A. Definition of a Markov-perfect equilibrium

We define by $I$ the set of all piecewise continuous functions from $[0, R_1]^2 \times [0, R_2]^{10} \to M$ to $R$. Note that due to the fact that we have a multi-mode game, a Markovian feedback strategy has to depend on the current states and the current mode. The strategy space of each firm is then given by $Z^2$.

Defining a Markov-perfect equilibrium in a multi-mode game is not completely standard. For a given strategy profile $\{I_{AB}\}_{i=1}^2$ we denote as $P_A$ the (stochastic) optimal control problem firm $A$ faces if the feedback rules $\{I_{1A}, I_{2B}\}$ are inserted for $\{I_{1B}, I_{2B}\}$. Note that after insertion of these strategies, the right hand side of the state dynamics depends on the mode $m(t)$. We define $\Xi$ as the set of all possible realizations of the random innovation time. Hence in the case of R&D competition we have $\Xi = [0, \omega]^2$, whereas under R&D cooperation $\Xi = [0, \omega]$. Following Dockner et al. (2000) we call a control path $u_f = (u_{1f}, u_{2f}) : [0, \omega] \times \Xi \to R^2$, where $f \in \{A, B\}$, feasible if

(i) $u_f$ is non-anticipating with respect to the realization of the project completion time. In the case of R&D competition this means that $u_f(t, \tau_A, \tau_B) = u_f(t) \forall \tau_A < \min[\tau_A, \tau_B]$ and $u_f(t, \tau_A, \tau_B) = u_f(t, \tau_A)$, for $\tau_A = \min[\tau_A, \tau_B]$ and $t = \tau_A \wedge \tau_B$ and $u_f(t, \tau_A, \tau_B) = u_f(t, \tau_A)$, for $\tau_A = \min[\tau_A, \tau_B]$ and $t = \tau_B$. Analogously for R&D cooperation:

(ii) the piecewise deterministic process $(K_{A}(\cdot), K_{1B}(\cdot), K_{2B}(\cdot), m(\cdot))$ is well-defined;

(iii) the constraints $K_f \ge 0$ and investment constraints (3) are satisfied with probability 1;

(iv) the objective integral is well-defined.

A feasible control path $u_f^*$ is optimal if it maximizes the objective integral within the set of all feasible control paths. Analogously we define the optimal path $u_f^0$.

Definition 1. A strategy profile $\{I_{1A}, I_{2A}, I_{1B}, I_{2B}\} \in 2^4$ is a Markov-perfect equilibrium (MPE) of the game if the following condition holds for each firm $f = A, B$:

- If the feedback strategies $\{I_{1f}, I_{2f}\}$ are applied to the control problem $P_f$ determined by inserting $\{I_{1f}, I_{2f}\}$, $g \neq f$, then the resulting (stochastic) investment process $(K_{1A}(\cdot), K_{2A}(\cdot), K_{1B}(\cdot), K_{2B}(\cdot), m(\cdot))$ coincides with the optimal path $u_f^0(t, \tau_A)$ with probability 1, where $\tau = (\tau_A, \tau_B)$ under R&D competition and $\tau = t$ under R&D cooperation.

Appendix B. Robustness checks

To check in how far the shape of the $\lambda^*$-curve is robust with respect to parameter changes other than those considered in Section 4.3 and to verify that the discussed shifts of the $\lambda^*$ curve triggered by parameter variations are not specific to the default set of parameters used in Section 4, in this appendix we reproduce Fig. 8 for two additional parameter settings. In Fig. 9 the chosen base parameter setting is

$$\lambda^{\text{comp}} = 0.05, \theta = 0.2, b_1 = b_2 = 0, c = 5, r = 0.04,$$

whereas in Fig. 10 we use

$$\lambda^{\text{comp}} = 0.05, \theta = 0, b_1 = b_2 = 1, c = 3, r = 0.04.$$
Fig. 9. Effect of the changes (a) in the discount rate, (b) in the capital adjustment cost parameter, and (c) in the vertical differentiation parameter on the arrival rate threshold $\lambda^*$ under the base parameter setting (12).

Fig. 10. Effect of the changes (a) in the discount rate, (b) in the capital adjustment cost parameter, and (c) in the vertical differentiation parameter on the arrival rate threshold $\lambda^*$ under the base parameter setting (13).
References


