

Horizontal and Vertical R&D Cooperation

Joachim Inkmann*

Department of Economics and Center of Finance and Econometrics (CoFE)
University of Konstanz, Box D124, 78457 Konstanz, Germany

Abstract: This paper introduces a second, vertically related industry into the usual one-industry oligopoly framework of cooperative R&D investment between firms operating on the same product market. R&D efforts are affected by intra- and inter-industry R&D spillovers. Horizontal and vertical R&D cooperation scenarios are compared to R&D competition. It turns out that vertical R&D cooperation is usually the only stable equilibrium in the sense that no firm has an incentive to chose any other R&D scenario. Empirical implications concerning the relationship between R&D intensities and R&D spillovers are derived and empirical evidence is given using data of German manufacturing firms.

Keywords: R&D cooperation; R&D spillovers; vertical relations

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1. Introduction

It is generally accepted that the incentives of firms to invest in research and development (R&D) are distorted because of the public good characteristic of new information. In particular, the appropriability problem has been widely discussed in the literature (cf. Spence, 1984, Cohen and Levinthal, 1989), which causes firms to underinvest in R&D because they can not completely internalize the social returns of their private efforts in the presence of R&D spillovers. Three instruments are usually considered to restore the firms' incentives to engage in R&D: Tax policies and direct subsidies, ex-post R&D cooperation through patents and licensing, and ex-ante R&D cooperation (cf. Katz and Ordover, 1990). While the first two instruments require government intervention to determine taxes and subsidies or to strengthen property rights, the third instrument is assumed to work through private incentives because of the possibility to internalize R&D spillovers between cooperating firms¹. Other advantages of R&D cooperation include the elimination of wasteful duplication of R&D efforts and the distribution of risk and fixed costs among participants (cf. Jacquemin, 1988).

Starting with the work by Katz (1986) and D'Aspremont and Jacquemin (1988) a large body of theoretical literature has emerged over the past decade trying to formalize firm's private incentives to engage in R&D cooperation by using oligopoly models which allow for strategic interactions between firms.² Usually, two-stage games are analyzed in which firms choose either noncooperatively or cooperatively their amount of R&D investment in the first stage and compete on the product market in the second stage. If R&D spillovers are sufficiently high this framework explains the private incentives for R&D cooperation between rivals which leads to increased R&D investment, output and social welfare. While these models differ in many details (e.g., Bertrand vs. Cournot competition in the second stage), they have in common that they focus on a single industry by analyzing intra-industry cooperation between rivals on the product market.

This stands in contrast to the large amount of empirical literature searching for both intra- and inter-industry R&D spillovers and claiming the particular importance of the latter for productivity growth (e.g. Griliches and Lichtenberg, 1984, and references cited in Capron et al., 1996). Descriptive evidence of R&D cooperation between sectors and within sectors re-

¹ Nevertheless, in many countries R&D cooperation is now explicitly supported by antitrust policy (for the EC, cf. Jacquemin, 1988, and Katsoulacos and Ulph, 1997).

² Examples include De Bondt and Veugelers (1991), Kamien et al. (1992), Suzumura (1992), Vonortas (1994), Ziss (1994), Salant and Shaffer (1998).

veals that inter-industry agreements are much more frequent than intra-industry agreements. According to Chesnais (1988), 80% of Japanese inter-firm R&D cooperation involve firms from different sectors. Licht (1994) presents similar evidence for six European countries. In these countries, the most prevalent form of R&D cooperation includes either customers or suppliers. Using German data from 1994, Harabi (1997) shows that 84% of all innovating firms are engaged in R&D cooperation with customers or suppliers. This form of cooperation is usually labeled vertical and distinguished from horizontal cooperation with firms operating in the same industry (cf. Geroski, 1992). Von Hippel (1986) and VanderWerf (1992) present case studies for the USA for innovations which are initiated by customers and suppliers, respectively. Von Hippel explains customer driven innovations by 'lead users' who have better capabilities to forecast their future needs or to fill their current needs than producers. VanderWerf argues that suppliers of intermediate goods have an incentive to encourage downstream innovation in order to increase their own demand. In both cases vertical cooperation in R&D may increase the innovative success of participating firms. Geroski (1992, 1995) points out that vertical R&D cooperation may be superior to horizontal agreements because the latter may lead to collusive pricing for the products embodying the joint R&D efforts.

Probably the most prominent example for the importance of vertical R&D cooperation between manufacturers and suppliers is the Japanese automotive industry. According to the results of the large scale 'International Motor Vehicle Program' conducted at the Massachusetts Institute of Technology and summarized in the influential book *The Machine that Changed the World* (Womack et al., 1990), the involvement of suppliers in early stages of the product development process was one source of the Japanese car industry's success. Womack et al. (p. 150) provide convincing evidence that '[...] the Japanese assembler gains from the increased willingness of its suppliers to come up with innovations and cost-saving suggestions and to work collaboratively.' This strategy of comprising the supplier's technological knowledge in the development process has become known under the label 'Early Supplier Involvement' (ESI). Figures presented by Clark and Fujimoto (1991) underline the relative importance of the supplier's contribution to the total development efforts devoted to a new car in the Japanese car industry which amounts to 30% compared to 16% in Europe and 7% in the USA. There is a considerable amount of evidence that Western car manufacturers have recognized this potential source of innovative success and extended their ESI strategies in response (cf. Lamming, 1993). Empirical evidence for the existence and significance of ESI strategies

outside the automotive industry is given by Bidault et al. (1998) who present examples from the electric appliances, consumer electronics and office equipment industries in the USA, Europe and Japan.

Given this strand of empirical literature highlighting the importance of vertical R&D cooperation, the limitation of the theoretical literature to one-industry oligopoly models explaining horizontal R&D cooperation between rivals is, at least, surprising. A first step towards weakening this theoretical limitation is done by Steurs (1995) who introduces a second industry into the D'Aspremont and Jacquemin framework which is related to the original industry by inter-industry R&D spillovers. He shows that inter-industry cooperation is more likely to increase R&D investment, output and total welfare than intra-industry R&D cooperation. Moreover, the private incentives for inter-industry R&D cooperation usually exceed the incentives to engage in intra-industry R&D arrangements unless inter-industry R&D spillovers are very small. While this model introduces inter-industry R&D cooperation, it can not explain vertical R&D cooperation between suppliers, manufacturers and customers because the two industries remain completely independent except for the presence of inter-industry R&D spillovers.

This assumption is given up in a second line of literature which considers strategic R&D investment in the presence of R&D spillovers between vertically related industries. Usually, the R&D investments of the firms in the upstream market affect either the production process or quality in the downstream market which encourages downstream demand and thereby the demand for the intermediate good produced in the upstream market. Harhoff (1991) analyzes a monopolist supplier reducing production costs of downstream firms, Peters (1995, 1997) considers an upstream oligopoly reducing downstream production costs, and Harhoff (1996) examines a monopolist supplier improving the product quality of downstream firms by strategic R&D investment. However, none of these studies explicitly accounts for the possibility of vertical R&D cooperation. Hence, a theoretical framework explaining a firm's incentives to engage in vertical R&D cooperation, e.g. by adopting ESI strategies, still seems to be missing.

This paper attempts to provide such a theoretical framework. To keep the theoretical model tractable, the simplifying assumptions of the models introduced by D'Aspremont and Jacquemin (1988) and Steurs (1995) are maintained. In particular, two duopoly industries are analyzed in which symmetric firms produce a homogeneous good. All firms can reduce their constant marginal production costs with certainty by investing in R&D. These investments are

affected by both intra- and inter-industry R&D spillovers. In addition, the two industries are vertically related by the ‘successive oligopoly’ structure developed by Greenhut and Ohta (1979) which is characterized by an upstream industry producing an intermediate good entering in fixed proportion the downstream firms’ production function. Their model has been criticized (e.g. by Waterson, 1982) for its fixed proportion assumption which rules out factor substitution in the downstream industry but is maintained here for its simplicity.

These assumptions lead to the following three-stage model: In the third stage downstream firms engage in Cournot competition given the price of the intermediate good and R&D investments in both industries. Solving the third stage equilibrium total industry output for the price of the intermediate good determines an inverse demand function for the second stage Cournot competition of the upstream firms given the R&D investments in both industries. In the first stage all firms simultaneously chose their R&D investments according to one of the following four R&D scenarios: R&D competition, horizontal intra-downstream and intra-upstream industry R&D cooperation, and vertical inter-industry R&D cooperation. It will be shown that vertical R&D cooperation is usually the only stable equilibrium in the sense that no firm has an incentive to chose any other R&D scenario.

In order to shed some light on the empirical content of the theoretical model, a small econometric investigation is carried out using data from German manufacturing firms collected in 1993. The empirical analysis focuses on the impact of intra- and inter-industry R&D spillovers on the R&D intensity of firms. For this task, a new empirical measure of intra- and inter-industry R&D spillovers is introduced which rests on the firms’ subjective evaluations of the probability that innovations are imitated. The theory predicts a negative effect of intra-industry spillovers and a positive effect of inter-industry spillovers on the R&D intensity for all firms except for those engaged in a horizontal R&D cooperation for which both effects are positive. The empirical analysis confirms the general sign pattern but can not reveal the exception concerning the firms participating in a horizontal R&D cooperation.

The outline of the paper is as follows. The output stages of the model are described in the next section. Section 3 analyzes in detail the different first stage R&D scenarios and derives the corresponding R&D investment levels. A comparison of the equilibrium values in R&D and output and of the associated profits is relegated to Section 4 which also derives some empirical implications of the theoretical model. Section 5 contains the empirical analysis and Section 6 concludes.

2. The Output Stages

The model describes two vertically related duopolies: the two firms located in the upstream industry produce an intermediate good which enters in fixed proportions the production function of the two firm's located in the downstream industry. The price of the intermediate good and the produced quantities of all firms are determined using the successive oligopoly structure proposed by Greenhut and Ohta (1979) in the second and third stage of the three-stage model given the firms' first stage R&D investments. R&D reduces with certainty the constant marginal production costs of the firms in both industries³ and is affected by intra- and inter-industry R&D spillovers which are quantified by the two parameters $0 \leq \beta \leq 1$ and $0 \leq \delta \leq 1$ in accordance with the two-industry model suggested by Steurs (1995). Denoting the R&D investments of the downstream firms by u_i ($i = 1, 2$) and the R&D investments of the upstream firms by v_i ($i = 1, 2$), the 'effective R&D investment' (cf. Kamien et al., 1992) which each firm would have to invest alone in the absence of spillovers to achieve the same unit cost reduction is defined as

$$U_i = u_i + \beta u_j + \delta(v_1 + v_2), \quad (i, j = 1, 2; i \neq j) \quad (1)$$

$$V_i = v_i + \beta v_j + \delta(u_1 + u_2), \quad (i, j = 1, 2; i \neq j) \quad (2)$$

in the downstream and upstream industry, respectively. Hence, the effective amount of R&D consists of the firm's own R&D investment, of the percentage β of the firm's competitor's R&D investment and of the fraction δ of the total R&D efforts conducted in the vertically related industry.

Upstream firms produce total homogeneous output $X = x_1 + x_2$ which is demanded by downstream firms for a price p which will be determined endogenously. Given the fixed proportion assumption, there is no loss of generality in setting the proportion parameter to one. Hence, the total downstream output can be also written as $X = x_1 + x_2$. In accordance with D'Aspremont and Jacquemin (1988, 1990) it is assumed that downstream firms face a linear inverse demand function $P = a - bX$ with $X \leq a/b$, $a, b > 0$, in their market. Denoting the marginal production costs in the downstream and upstream industry by c and d , respectively,

³ Thus, it is assumed that R&D efforts lead with certainty to cost reducing process innovations. Alternatively, one could argue that product quality improving product innovations are the primary goal of the firms' R&D efforts. However, in an extension of the D'Aspremont and Jacquemin model covering both process and product related R&D investment, Kaiser and Licht (1998) show that the theoretical implications for both types of R&D are very similar.

with $c > 0$, $d > 0$, $c \geq U_i$, $d \geq V_i$ and $a - c - d > 0$, and assuming diminishing returns in R&D measured by the parameter γ , the profit functions can be written as

$$\Pi_i^d = (a - bX - p - c + U_i)x_i - (\gamma/2)u_i^2, \quad (i = 1,2) \quad (3)$$

$$\Pi_i^u = (p - d + V_i)x_i - (\gamma/2)v_i^2, \quad (i = 1,2) \quad (4)$$

where downstream and upstream firm are distinguished by the superscripts d and u. Imposing $p = 0$ on (3) yields the profit function of a firm in the model of Steurs (1995) who considers two independent industries. Imposing in addition $\delta = 0$ on (1) yields the profit function employed in the original D'Aspremont and Jacquemin (1988) one-industry model.

Solving the model by means of backward induction the third stage of the model is solved first in which downstream firms engage in Cournot competition given the price of the intermediate good and the R&D investment levels in both industries. The first order conditions for a maximum of Π_i^d with respect to x_i have the form ($i, j = 1,2; i \neq j$)

$$\frac{\partial \Pi_i^d}{\partial x_i} = \frac{a-c}{2b} - x_i - \frac{1}{2}x_j - \frac{1}{2b}p + \frac{1}{2b}u_i + \frac{\beta}{2b}u_j + \frac{\delta}{2b}(v_1 + v_2) = 0 \quad (4)$$

and define the reaction function of the two downstream firms. The second order conditions $\partial^2 \Pi_i^d / \partial x_i^2 < 0$ are obviously satisfied. The reaction functions are well behaved in the sense that they satisfy the sufficient condition $\partial^2 \Pi_i^d / \partial x_i^2 + |\partial^2 \Pi_i^d / \partial x_i \partial x_j| < 0$ for a unique Cournot equilibrium. This condition also implies the existence and stability of the resulting Cournot equilibrium (cf. Friedman, 1977, p. 71, A7).⁴ The third stage equilibrium output x_i^{III} follows from (4) by replacing x_j with its reaction function

$$x_i^{\text{III}} = \frac{a-c}{3b} - \frac{1}{3b}p + \frac{2-\beta}{3b}u_i + \frac{2\beta-1}{3b}u_j + \frac{\delta}{3b}(v_1 + v_2). \quad (i, j = 1,2; i \neq j) \quad (5)$$

The produced quantity of firm i unambiguously increases with its own R&D investment and with the amount of R&D conducted by the firms located in the upstream industry. It decreases with an increasing price of the intermediate good and with increasing R&D investments of the competitor unless intra-industry R&D spillovers are sufficiently high ($\beta > 0.5$).

⁴ These uniqueness, existence and stability statements hold under certain assumptions regarding the shapes of the demand and cost functions (cf. Friedman, 1977, pp. 19-20, A1 and A2) which are satisfied in the linear case analyzed here.

The successive oligopoly structure suggested by Geenhut and Ohta (1979) relies on solving the total third stage industry output $X^{\text{III}} = x_i^{\text{III}} + x_j^{\text{III}}$ for the price p of the intermediate good. Using this procedure the price of the intermediate good and thereby the inverse demand function for the second stage Cournot game of the upstream firms is endogenously determined by the model. This is an advantage over the vertically related two industry model proposed by Peters (1995, 1997) who also assumes a fixed proportions downstream production function but treats the price of the intermediate good as exogenous.⁵ Proceeding as described above the inverse demand function for the upstream industry results as

$$p = a - c - \frac{3b}{2}(x_i^{\text{III}} + x_j^{\text{III}}) + \frac{1+\beta}{2}(u_i + u_j) + \delta(v_1 + v_2). \quad (i, j = 1, 2; i \neq j) \quad (6)$$

Replacing p in the upstream profit functions Π_i^{U} ($i = 1, 2$) given in (4) with (6) defines the second stage objective functions of the upstream firms which also engage in Cournot competition. The first order conditions for profit maximization satisfy ($i, j = 1, 2; i \neq j$)

$$\frac{\partial \Pi_i^{\text{U}}}{\partial x_i} = \frac{a - c - d}{3b} - x_i - \frac{1}{2}x_j + \frac{1+\delta}{3b}v_i + \frac{\beta + \delta}{3b}v_j + \frac{1+\beta + 2\delta}{6b}(u_1 + u_2) = 0 \quad (7)$$

and define the two reaction functions of the upstream firms. The second order condition as well as the sufficient condition for a unique Cournot equilibrium are again satisfied as can be readily seen. Hence, a stable Cournot equilibrium exists which is characterized by the produced quantities ($i, j = 1, 2; i \neq j$)

$$x_i^{\text{II}} = \frac{2(a - c - d)}{9b} + \frac{2(2 - \beta + \delta)}{9b}v_i + \frac{2(2\beta - 1 + \delta)}{9b}v_j + \frac{1 + \beta + 2\delta}{9b}(u_1 + u_2) \quad (8)$$

obtained from replacing x_j in (7) with its reaction function and solving for x_i . Similar to the results established for the downstream industry, the produced quantity of upstream firm i increases with its own R&D investment and the R&D efforts of the downstream industry and decreases with the R&D investments of its competitor unless overall R&D spillovers are sufficiently high ($2\beta + \delta > 1$).

Substitution of $(x_i^{\text{III}} + x_j^{\text{III}})$ in (6) with $(x_i^{\text{II}} + x_j^{\text{II}})$ determines the price of the intermediate good in terms of R&D investment

⁵ Actually, Peters (1995) recommends weakening this exogeneity assumption in future research.

$$p = \frac{a-c+2d}{3} + \frac{1+\beta-4\delta}{6}(u_i+u_j) - \frac{1+\beta-\delta}{3}(v_1+v_2), \quad (i, j=1,2; i \neq j) \quad (9)$$

which decreases with increasing R&D investment of the upstream firms. Therefore the own cost reducing effect of upstream R&D exceeds the effect of an increased demand for the intermediate good in the downstream industry due to the cost reducing inter-industry spillovers. The price of the intermediate good increases with downstream R&D investment of downstream firms if $(1+\beta) > 4\delta$.

Combining (5) with (9), the produced quantities of the downstream firms can be expressed exclusively in terms of R&D as $(i, j=1,2; i \neq j)$

$$x_i^{\text{III}} = \frac{2(a-c-d)}{9b} + \frac{11-7\beta+4\delta}{18b}u_i + \frac{11\beta-7+4\delta}{18b}u_j + \frac{1+\beta+2\delta}{9b}(v_1+v_2). \quad (10)$$

Due to the fixed (one to one) proportions assumption, the Cournot industry outputs are equal in both industries, i.e. $X^{\text{II}} = x_i^{\text{II}} + x_j^{\text{II}} = x_i^{\text{III}} + x_j^{\text{III}} = X^{\text{III}}$. Substitution of (9) and (10) in Π_i^{d} ($i=1,2$) defined in (3) yields the indirect profit function for the downstream firms which is maximized in the first stage of the game with respect to R&D investments u_i . Correspondingly, substituting (8) and (9) in Π_i^{u} ($i=1,2$) defined in (4) yields the indirect profit function for the upstream firms which is maximized in the first stage of the game with respect to R&D investments v_i .

3. The R&D Stage

The indirect first stage profit functions in both industries can be expressed as $(i, j=1,2; i \neq j)$

$$\begin{aligned} \Pi_i^{\text{d}} &= (a - bX^{\text{III}} - p - c + U_i)x_i^{\text{III}} - (\gamma/2)u_i^2, \\ &= \frac{4}{9}b \left[Z + \frac{1}{4}(5A - B)u_i + \frac{1}{4}(5B - A)u_j + \frac{1}{2}(A + B)(v_1 + v_2) \right]^2 - b\Gamma u_i^2, \end{aligned} \quad (11)$$

$$\begin{aligned} \Pi_i^{\text{u}} &= (p - d + V_i)x_i^{\text{II}} - (\gamma/2)v_i^2, \\ &= \frac{2}{3}b \left[Z + Av_i + Bv_j + \frac{1}{2}(A + B)(u_1 + u_2) \right]^2 - b\Gamma v_i^2, \end{aligned} \quad (12)$$

where $Z = (a-c-d)/3b$, $A = (2-\beta+\delta)/3b$, $B = (2\beta-1+\delta)/3b$, and $\Gamma = \gamma/2b$ are introduced for notational convenience. In the first stage of the game the firms maximize their profits, either noncooperatively or cooperatively, with respect to R&D investments. An R&D cooperation is defined by a maximization of the joined profit which is the sum of the profits

of the cooperating firms. The output stages remain unaffected by an R&D cooperation which means that cooperating firms within the same industry remain competitors in quantities. Four R&D scenarios are distinguished in this section: R&D competition (NC), intra-downstream industry R&D cooperation (DC), intra-upstream industry R&D cooperation (UC) and inter-industry R&D cooperation (IC). The following paragraphs derive the corresponding symmetric Nash equilibria in R&D. A comparison of the R&D outcomes and the associated quantities and profits is relegated to Section 4.⁶

R&D Competition (NC)

In the competitive scenario each firm independently maximizes its indirect profit function with respect to its R&D investment. The first order condition for a maximum of the downstream profit function (11) can be written as ($i, j = 1, 2; i \neq j$)

$$\begin{aligned} \frac{\partial \Pi_i^d}{\partial u_i} = & 4(5A - B)Z + \left((5A - B)^2 - 36\Gamma \right) u_i + (5A - B)(5B - A)u_j \\ & + 2(5A - B)(A + B)(v_1 + v_2) = 0. \end{aligned} \quad (13)$$

R&D efforts conducted in the upstream industry always serve as a strategic complement (cf. Bulow et al., 1985) for a downstream firm's own R&D investment while the R&D investment of the firm's competitor is a strategic substitute unless overall R&D spillovers are sufficiently high ($5B > A \Leftrightarrow 11\beta + 4\delta > 7$).

Here and in the following it is assumed that Γ is sufficiently large to ensure that the second order condition for profit maximization is satisfied. This assumption is also sufficient for the existence of the Cournot equilibrium in R&D (cf. Friedman, 1977, p. 71). The sufficient condition for uniqueness is $\partial^2 \Pi_i^d / \partial u_i^2 + |\partial^2 \Pi_i^d / \partial u_i \partial u_j| + \sum_{j=1}^2 |\partial^2 \Pi_i^d / \partial u_i \partial v_j| < 0$ and also implies stability of the Cournot equilibrium in R&D (cf. Friedman, 1977, p. 71). This condition states that the firm's own R&D investment effect on its reaction function dominates the joined impact of the other firms' R&D investments in absolute value. Unfortunately, this condition is a complicated nonlinear function of the model parameters which is difficult to interpret. The model shares this property with all studies within the D'Aspremont and Jacquemin framework. A detailed stability analysis of their original model is presented by Henriques

⁶ In contrast to the original contributions by D'Aspremont and Jacquemin (1988, 1990) and Steurs (1995), welfare considerations are omitted in the current paper which focuses on the firms' private incentives to engage in R&D cooperation.

(1990). Even in this basic model the stability condition is too complicated to derive simple expressions for the spillover parameters as a function of the other exogenous model parameters for which a stable equilibrium fails to exist. Therefore, Henriques refers to a simulation of the model which assigns some numerical values to these other model parameters. In this example she detects (small) unstable regions in the spillover parameter space. However, her results depend crucially on the specific parameterization which prevents any further application of her findings. Thus, in accordance with the existing extensions of the D'Aspremont and Jacquemin model in which the stability issue is addressed (e.g. De Bondt and Veugelers, 1991, Kamien et al., 1992, Suzumura, 1992, Vonortas, 1994, and Steurs, 1995), the stability condition is imposed without explaining its content in more detail.

The first order condition for a maximum of the upstream profit function (12) in the non-cooperative R&D scenario can be written as ($i, j = 1, 2; i \neq j$)

$$\frac{\partial \Pi_i^u}{\partial v_i} = 2AZ + (2A^2 - 3\Gamma)v_i + 2ABv_j + A(A + B)(u_1 + u_2) = 0. \quad (14)$$

The second order and stability conditions are assumed to hold. The strategic effects are similar to those in the downstream industry: downstream R&D efforts are strategic complements and stimulate the upstream firm's R&D investment while the competitors' R&D investments work as a strategic substitute unless overall spillovers are high ($B > 0 \Leftrightarrow 2\beta + \delta > 1$). The same condition is obtained by Steurs (1995) for two independent industries. It is less demanding than the condition for strategic complements within the downstream industry.

Focusing on a symmetric Nash equilibrium in R&D and therefore dropping the index, the reaction functions (13) and (14) reduce to

$$\begin{aligned} 9\Gamma u &= (5A - B)[Z + (A + B)(u + v)], \\ 9\Gamma v &= 2A[Z + (A + B)(u + v)]. \end{aligned} \quad (15)$$

Solving (15) for the Nash equilibrium R&D levels in the noncooperative scenario leads to⁷

$$u_{NC}^N = \frac{(5A - B)Z}{9\Gamma - (7A - B)[A + B]}, \quad (16)$$

⁷ In all scenarios the optimal reaction functions have the form $9\Gamma u = a[Z + (A+B)(u+v)]$ and $9\Gamma v = b[Z + (A+B)(u+v)]$ and imply the Nash equilibria $u^N = aZ/(9\Gamma - (a+b)[A+B])$ and $v^N = bZ/(9\Gamma - (a+b)[A+B])$.

$$v_{NC}^N = \frac{2AZ}{9\Gamma - (7A - B)[A + B]}.$$

In equilibrium, downstream firms conduct more R&D than upstream firms.

Horizontal R&D Cooperation in the Downstream Industry (DC)

The first cooperative R&D scenario is characterized by a horizontal R&D cooperation of the two downstream firms while upstream firms remain competitors in R&D. Hence, an upstream firm's reaction function under symmetry is given in (15). Downstream firms maximize their joined profits $\Pi^{DC} = \Pi_i^d + \Pi_j^d$ over their respective R&D investment levels. The first order condition satisfies ($i, j = 1, 2; i \neq j$)

$$\begin{aligned} \frac{\partial \Pi^{DC}}{\partial u_i} = 16(A + B)Z + \left((5A - B)^2 + (5B - A)^2 - 36\Gamma \right) u_i \\ + 2(5A - B)(5B - A)u_j + 8(A + B)^2(v_1 + v_2) = 0. \end{aligned} \quad (17)$$

The second order and stability conditions are assumed to be satisfied. The signs of the strategic effects are the same as in the noncooperative scenario. Imposing symmetric R&D investments within the two industries, the reaction function (17) can be written as

$$9\Gamma u = 4(A + B)[Z + (A + B)(u + v)] \quad (18)$$

and implies, in combination with the upstream reaction function given in (15), the following equilibrium R&D investments

$$\begin{aligned} u_{DC}^N &= \frac{4(A + B)Z}{9\Gamma - (6A + 4B)[A + B]}, \\ v_{DC}^N &= \frac{2AZ}{9\Gamma - (6A + 4B)[A + B]}. \end{aligned} \quad (19)$$

Again, the R&D efforts of the downstream firms exceed those of the upstream firms.

Horizontal R&D Cooperation in the Upstream Industry (UC)

In the second horizontal R&D cooperation scenario upstream firms cooperate in R&D while downstream firms remain competitors. Hence, a downstream firm's reaction function under symmetry is given in (15). The firms located in the upstream industry maximize their joined

profits $\Pi^{UC} = \Pi_i^u + \Pi_j^u$ over their respective R&D investment levels. The first order condition satisfies ($i, j=1,2; i \neq j$)

$$\frac{\partial \Pi^{UC}}{\partial v_i} = 2(A+B)Z + (2(A^2 + B^2) - 3\Gamma)v_i + 4ABv_j + (A+B)^2(u_1 + u_2) = 0. \quad (20)$$

The second order and stability conditions are assumed to hold. The signs of the strategic effects are the same as in the noncooperative scenario. Imposing symmetric R&D investments within the two industries, the reaction function (20) can be written as

$$9\Gamma v = 6(A+B)[Z + (A+B)(u+v)] \quad (21)$$

and implies, in combination with the downstream reaction function given in (15), the following equilibrium R&D investments

$$u_{UC}^N = \frac{(5A-B)Z}{9\Gamma - (11A+5B)[A+B]}, \quad (22)$$

$$v_{UC}^N = \frac{6(A+B)Z}{9\Gamma - (11A+5B)[A+B]}.$$

If overall R&D spillovers are sufficiently high, $(6A+6B > 5A-B) \Leftrightarrow (13\beta+8\delta > 5)$, upstream firms conduct more R&D than downstream firms.

Vertical R&D Cooperation (VC)

In the vertical R&D cooperation scenario one downstream firm cooperates with one upstream firm. Because the two firms within both industries are completely symmetric they should behave symmetrically. Hence, two pairs of vertical R&D cooperation are analyzed. Assuming that the two first and the two second firms in each industry cooperate⁸, all firms maximize the joined profits $\Pi^{VC} = \Pi_i^d + \Pi_i^u$, ($i=1,2$). The first order conditions for profit maximization are ($i, j=1,2; i \neq j$)

$$\frac{\partial \Pi^{VC}}{\partial u_i} = 8(4A+B)Z + ((5A-B)^2 + 6(A+B)^2 - 36\Gamma)u_i + ((5A-B)(5B-A) + 6(A+B)^2)u_j + (2(5A-B)(A+B) + 12A(A+B))v_1 + (2(5A-B)(A+B) + 12B(A+B))v_2 = 0 \quad (23)$$

⁸ This assumption is not restrictive because only symmetric Nash equilibria in R&D are derived.

for a firm located in the downstream industry and

$$\begin{aligned} \frac{\partial \Pi^{VC}}{\partial v_i} = & 4(4A + B)Z + (12A^2 - 2(A + B)^2 - 18\Gamma)v_i + (12AB + 2(A + B)^2)v_j \\ & + ((5A - B)(A + B) + 6A(A + B))u_1 + ((5B - A)(A + B) + 6A(A + B))u_2 = 0 \end{aligned} \quad (24)$$

for an upstream firm. The second order and stability conditions are assumed to be satisfied in both industries. Unlike the competitive and the horizontal cooperation scenarios, the R&D investments of the competing firm in the same industry always work as a strategic complement to each firm's own R&D efforts. The same holds for the R&D investments of the firms located in the other industry which was found in all R&D scenarios. However, the strategic effects of the two firms in the vertically related industry have a different magnitude: the strategic effect of the cooperation partner exceeds the effect of the second firm in the vertically related industry.

Imposing symmetry on the R&D investments within each industry, the reaction functions (23) and (24) can be drastically simplified to

$$9\Gamma u = 9\Gamma v = 2(4A + B)[Z + (A + B)(u + v)] \quad (25)$$

which implies the following equilibrium R&D investments

$$u_{VC}^N = v_{VC}^N = \frac{2(4A + B)Z}{9\Gamma - (16A + 4B)[A + B]}. \quad (26)$$

Hence, in contrast to the R&D scenarios considered before, the downstream and upstream firms engaging in a vertical R&D cooperation invest the same amount of R&D.

4. Comparing the R&D Scenarios

The Nash equilibrium values in R&D of the different R&D scenarios $S = (NC, DC, UC, VC)$ in the first stage of the game have a common structure which can be expressed as

$$\begin{aligned} u_S^N &= \frac{(a_S^d A + b_S^d B)Z}{9\Gamma - (a_S A + b_S B)[A + B]}, \\ v_S^N &= \frac{(a_S^u A + b_S^u B)Z}{9\Gamma - (a_S A + b_S B)[A + B]}, \end{aligned} \quad \text{with} \quad \begin{aligned} a_S &= a_S^d + a_S^u, \\ b_S &= b_S^d + b_S^u. \end{aligned} \quad (27)$$

Evaluating the second stage Cournot-Nash equilibrium output given in (8), or the third stage equilibrium output given in (10), after introducing symmetry in R&D investment ($u = u_i = u_j$, $v = v_1 = v_2$) yields the equilibrium quantities for the scenarios $S = (\text{NC}, \text{DC}, \text{UC}, \text{VC})$ which can be written as

$$x_S^N = \frac{6\Gamma Z}{9\Gamma - (a_S^d A + b_S^d B)[A + B]}. \quad (28)$$

Using (27) and (28) it is straightforward to compute the R&D intensities

$$\bar{u}_S^N \equiv \frac{u_S^N}{x_S^N} = \frac{a_S^d A + b_S^d B}{6\Gamma}, \quad \bar{v}_S^N \equiv \frac{v_S^N}{x_S^N} = \frac{a_S^u A + b_S^u B}{6\Gamma}, \quad (29)$$

for the different cooperation scenarios $S = (\text{NC}, \text{DC}, \text{UC}, \text{VC})$. Finally, the equilibrium profits

$$\Pi_S^{dN} = b(x_S^N)^2 - b\Gamma(u_S^N)^2, \quad \Pi_S^{uN} = \frac{3}{2}b(x_S^N)^2 - b\Gamma(v_S^N)^2, \quad (30)$$

can be obtained from evaluating (11) and (12) at (27) for $S = (\text{NC}, \text{DC}, \text{UC}, \text{VC})$. The weights $a_S^d, b_S^d, a_S^u, b_S^u$ given in the proceeding expressions can be obtained from the previous section and are summarized again in the following table.

Table 1.
Description of the Equilibria

S	Description of the R&D scenario	a_S^d	b_S^d	a_S^u	b_S^u
NC	R&D competition	5	-1	2	0
DC	Horizontal downstream industry R&D cooperation	4	4	2	0
UC	Horizontal upstream industry R&D cooperation	5	-1	6	6
VC	Vertical R&D cooperation	8	2	8	2

A ranking of the equilibrium values (27) – (30) over those scenarios which are under a firm's influence, i.e. $S = (\text{NC}, \text{DC}, \text{VC})$ for downstream firms and $S = (\text{NC}, \text{UC}, \text{VC})$ for upstream firms, is of particular interest for a description of the firm's production and R&D incentives. A comparison of equilibrium quantities and R&D intensities between the different scenarios is simple because either the numerator or the denominator is independent of $S = (\text{NC}, \text{DC}, \text{UC}, \text{VC})$. A comparison of the R&D levels in two scenarios becomes difficult if both numerator and denominator are larger in one of the two scenarios under consideration.

Fortunately, this is only the case if one compares v_{VC}^N with v_{UC}^N . This comparison depends on the magnitude of b and γ through Γ while all other values can be ordered independent on the magnitude of the exogenous parameters a, b, c, d, γ . Summarizing some tedious but simple calculations the following ranking of the equilibrium quantities, R&D investments and intensities can be established:

downstream industry

$$\begin{aligned} (x_{VC}^N, u_{VC}^N, \bar{u}_{VC}^N) &> (x_{DC}^N, u_{DC}^N, \bar{u}_{DC}^N) > (x_{NC}^N, u_{NC}^N, \bar{u}_{NC}^N) && (5B > A) \Leftrightarrow (11\beta + 4\delta > 7), \\ (x_{VC}^N, u_{VC}^N, \bar{u}_{VC}^N) &> (x_{DC}^N, u_{DC}^N, \bar{u}_{DC}^N) = (x_{NC}^N, u_{NC}^N, \bar{u}_{NC}^N) && \text{if } (5B = A) \Leftrightarrow (11\beta + 4\delta = 7), \\ (x_{VC}^N, u_{VC}^N, \bar{u}_{VC}^N) &> (x_{NC}^N, u_{NC}^N, \bar{u}_{NC}^N) > (x_{DC}^N, u_{DC}^N, \bar{u}_{DC}^N) && (5B < A) \Leftrightarrow (11\beta + 4\delta < 7), \end{aligned}$$

upstream industry

$$\begin{aligned} x_{VC}^N &> x_{UC}^N > x_{NC}^N, && \bar{v}_{VC}^N > \bar{v}_{UC}^N > \bar{v}_{NC}^N && (2B < A) \Leftrightarrow (5\beta + \delta < 4), \\ v_{VC}^N &> v_{UC}^N > v_{NC}^N && \text{if } (2B \leq A) \Leftrightarrow (5\beta + \delta \leq 4), && \bar{v}_{VC}^N = \bar{v}_{UC}^N > \bar{v}_{NC}^N && \text{if } (2B = A) \Leftrightarrow (5\beta + \delta = 4), \\ v_{VC}^N, v_{UC}^N &> v_{NC}^N && (2B > A) \Leftrightarrow (5\beta + \delta > 4), && \bar{v}_{UC}^N > \bar{v}_{VC}^N > \bar{v}_{NC}^N && (2B > A) \Leftrightarrow (5\beta + \delta > 4). \end{aligned}$$

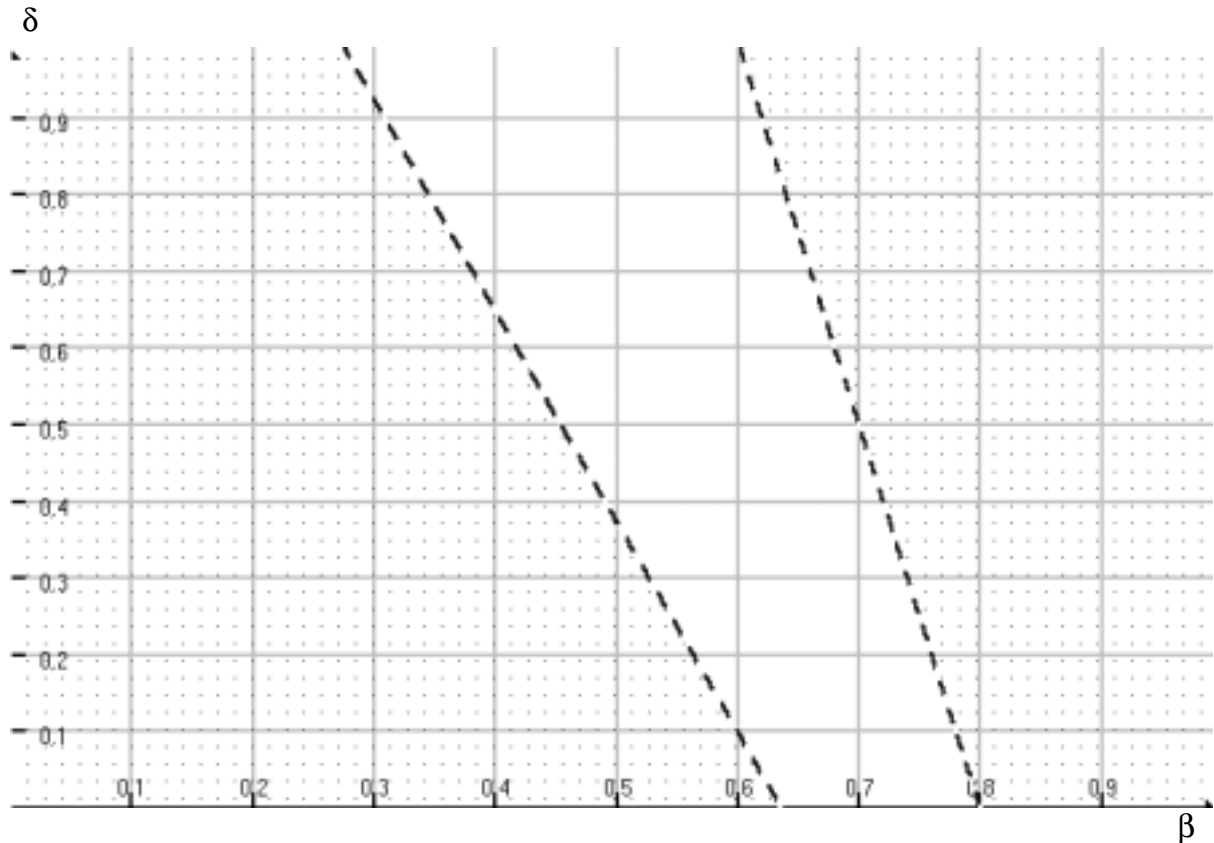
The ranking of the profits in the different scenarios is also independent of the parameters a, c, d in Z but depends in a complicated way on the parameters b and γ in Γ . Therefore, following the approach proposed by Steurs (1995), the equilibrium profits are simulated by varying the two spillover parameters β, δ in steps of 0.1 over their parameter space $[0,1] \times [0,1]$ for given values of the parameters a, b, c, d, γ . This procedure is repeated for different values of b and γ .⁹ The simulations reveal that the profits in most cases display exactly the same ranking as the quantities given above. This result implies that vertical inter-industry R&D cooperation is usually the only stable equilibrium in this game in the sense that neither downstream nor upstream firms have an incentive to choose any other scenario. If the spillover parameters are of a magnitude such that $A \in (2B, 5B)$ is satisfied, then the output and R&D investment levels associated with the stable vertical R&D cooperation scenario exceed the respective levels of the other scenarios in both industries.

These results can be presented in a simple figure. The spillover parameter space presented in Figure 1 is divided into three regions by the two implicit functions $A = 5B$ and $A = 2B$. In this graph, the parameter space is spanned by the intra-industry spillover parameter β in the horizontal dimension and the inter-industry spillover parameter δ in the vertical dimension. The left dashed line in the figure corresponds to $A = 5B$ and the right line to

⁹ The simulations were performed using a Gauss program which is available upon request from the author.

$A = 2B$. The bright region between these two lines represents parameter constellations, e.g. $\beta = \delta = 0.5$, for which output, R&D investments and intensities are maximized in the vertical R&D cooperation scenario and minimized in the noncooperative R&D scenario in both industries while the corresponding equilibrium values of the horizontal scenarios fall in between. The same ordering usually applies to the profits.

Figure 1. Regions of Cooperative R&D in the Spillover Parameter Space



Compared to the middle region, $A \in (2B, 5B)$, spillover parameter constellations in the shaded region below the left line ($A > 5B$), e.g. $\beta = \delta = 0.25$, only affect the downstream industry equilibrium value ranking. In this region the noncooperative R&D scenario becomes more attractive for downstream firms than the intra-industry cooperation scenario in the sense that the associated profits are higher. However, both remain dominated by the profits achieved in the vertical R&D scenario. The same ordering holds for the downstream firms R&D investment level. This can be explained by (17) which implies that the strategic effect of the competitor's R&D investment on the downstream firm's reaction function becomes negative below the left line if both firms cooperate in R&D. Hence, the competitor's R&D investment serves as a strategic substitute while it is a strategic complement in the middle region. The

R&D intensities and the produced quantities of the downstream firms in the noncooperative scenario also exceed their respective equilibrium values in the horizontal R&D cooperation scenario if the overall R&D spillovers are sufficiently low.

Any combination of the spillover parameters β and δ falling in the shaded region above the right line ($A < 2B$) in Figure 1, e.g. $\beta = \delta = 0.75$, changes the equilibrium level ordering in the upstream industry while the downstream industry ranking is the same as in the middle region. However, only the ranking of the R&D investments and intensities of the upstream firms is affected. The ordering of the produced quantities and of the profits remains unchanged. While the relative magnitude of the R&D investment levels v_{UC}^N and v_{VC}^N is unclear without further assumptions on Γ as described above, the R&D intensity of the horizontal intra-upstream cooperation scenario, \bar{v}_{UC}^N , exceeds the R&D intensity of the vertical cooperation scenario, \bar{v}_{VC}^N , if $2B > A$.

Empirical Implications

The subsequent empirical analysis focuses on the relationship between R&D spillovers and R&D investments which has played a key role in both the theoretical and empirical literature on R&D since its very beginning (e.g. Spence, 1984). The model outlined above enriches this discussion because it provides a framework in which intra- and inter-industry spillovers are distinguished and noncooperative and cooperative R&D outcomes are derived. Hence, the model supplies explicit hypotheses about the impact of the two types of R&D spillovers on a firm's R&D engagement given the firm decides independently on R&D or jointly with a cooperating firm operating on the same market or working in a vertical relationship. Focussing on the R&D intensity as the R&D variable usually employed in empirical work, the following marginal effects of the spillover parameters on the R&D intensity in the different cooperation scenarios can be obtained from (29).

Impact of intra-industry spillovers (31)

$$\begin{aligned} \frac{\partial \bar{u}_{NC}^N}{\partial \beta} &= -\frac{7}{9\gamma Z} < 0, & \frac{\partial \bar{u}_{DC}^N}{\partial \beta} &= \frac{4}{9\gamma Z} > 0, & \frac{\partial \bar{u}_{UC}^N}{\partial \beta} &= -\frac{7}{9\gamma Z} < 0, & \frac{\partial \bar{u}_{VC}^N}{\partial \beta} &= -\frac{4}{9\gamma Z} < 0, \\ \frac{\partial \bar{v}_{NC}^N}{\partial \beta} &= -\frac{2}{9\gamma Z} < 0, & \frac{\partial \bar{v}_{DC}^N}{\partial \beta} &= -\frac{2}{9\gamma Z} < 0, & \frac{\partial \bar{v}_{UC}^N}{\partial \beta} &= \frac{6}{9\gamma Z} > 0, & \frac{\partial \bar{v}_{VC}^N}{\partial \beta} &= -\frac{4}{9\gamma Z} < 0. \end{aligned}$$

Impact of inter-industry spillovers (32)

$$\begin{aligned} \frac{\partial \bar{u}_{NC}^N}{\partial \delta} &= \frac{4}{9\gamma Z} > 0, & \frac{\partial \bar{u}_{DC}^N}{\partial \delta} &= \frac{8}{9\gamma Z} > 0, & \frac{\partial \bar{u}_{UC}^N}{\partial \delta} &= \frac{4}{9\gamma Z} > 0, & \frac{\partial \bar{u}_{VC}^N}{\partial \delta} &= \frac{10}{9\gamma Z} > 0, \\ \frac{\partial \bar{v}_{NC}^N}{\partial \delta} &= \frac{2}{9\gamma Z} > 0, & \frac{\partial \bar{v}_{DC}^N}{\partial \delta} &= \frac{2}{9\gamma Z} > 0, & \frac{\partial \bar{v}_{UC}^N}{\partial \delta} &= \frac{12}{9\gamma Z} > 0, & \frac{\partial \bar{v}_{VC}^N}{\partial \delta} &= \frac{10}{9\gamma Z} > 0. \end{aligned}$$

It is obvious from (31) that increasing intra-industry spillovers reduce a firm's incentive to invest in R&D except for the case in which the firm is engaged in a horizontal intra-industry R&D cooperation. In the latter case the firm's R&D intensity increases with increasing intra-industry R&D spillovers. This result holds symmetrically for both the downstream and upstream industry. The sign pattern for the impact of inter-industry spillovers on R&D intensities is also identical in both industries. Increasing inter-industry R&D spillovers always encourage a firm's R&D intensity regardless on the underlying R&D scenario. These qualitative hypotheses are subject to the empirical analysis in the next section.

5. Empirical Evidence

The scope of this section is limited to the empirical content of the qualitative theoretical results derived above. It is not intended to estimate structural form equations of the theoretical model which would be too ambitious given the simplifying assumptions of the oligopoly game (e.g. symmetry of firms). In accordance with Slade (1995), the static theoretical model is used as a tool to 'provide useful summary statistics concerning the outcomes of oligopolistic interactions' (p. 369). Reduced form R&D intensity equations are estimated to achieve some insight if these outcomes are reflected in real data.

The empirical analysis is based on the first wave of the Mannheim Innovation Panel (MIP) collected in 1993 by the Centre for European Economic Research in Mannheim in charge of the German Ministry of Education, Research and Technology.¹⁰ The data set covers about 3,000 firms in the manufacturing, construction and service sectors. Excluding the latter sector which is difficult to embed in the theoretical framework of the previous sections and deleting missing values of the variables of interest described in the next paragraphs, a sample of 1,758 firms remains for the regressions.

¹⁰ The questionnaire follows the guidelines for the standardization of innovation surveys proposed by OECD (1997) in the so called 'Oslo-Manual'. The first wave of the MIP serves as Germany's contribution to the European Community Innovations Surveys (CIS; cf. Harhoff and Licht, 1994, for details).

The first wave of the MIP contains extensive information about the R&D and innovation activities of the firms. These include the R&D intensity defined as the ratio of R&D expenditures to sales and indicators for horizontal and vertical R&D cooperation agreements. The R&D intensity variable is censored because about 30% (= 546) of the firms included in the final sample report an R&D intensity of zero. One might argue that these firms could be omitted for the current purpose. However, 16 of these firms report a vertical R&D cooperation as shown in Table 2.

Table 2.
Distribution of R&D Cooperation Scenarios

	none	horizontal	vertical	both	sum
All firms	1384 (78.72)	33 (1.88)	289 (16.44)	52 (2.96)	1758 (100.00)
R&D participants	854 (70.46)	33 (2.72)	273 (22.52)	52 (4.29)	1212 (100.00)

Source: Mannheim Innovation Panel (MIP), first wave 1993. Numbers in parentheses are row percentages.

The dominance of vertical R&D cooperation over horizontal R&D cooperation which has initiated the theoretical model is readily seen from this table. It also becomes apparent that the theoretical model can not explain this distribution of cooperation scenarios because the theory implies that firms have no incentive to chose any other cooperation form than the vertical R&D cooperation scenario. Therefore, additional reasons must exist to chose a particular R&D scenario which are not covered by the model. It is assumed here that these reasons may influence a firm's cooperation choice but do not affect the magnitude of a firm's R&D intensity in a given scenario. Using this assumption, an empirical investigation of the theoretical hypotheses derived above remains possible.

This investigation is rendered difficult by the impossibility to observe the two R&D spillover parameters of interest, β and δ . D'Aspremont and Jacquemin (1990, p. 641) address this issue as follows: 'In terms of empirical verification [...], it is [...] crucial to extend the analysis [...] of cooperative R&D by taking into account the main determinants that can modify, at one moment of time, the level of the corresponding externalities.' Empirical R&D spillover variables which were constructed to meet this requirement are numerous and over-viewed, e.g., by Griliches (1992), Nadiri (1993) and Inkmann and Pohlmeier (1995). Most authors construct so called 'R&D spillover pool' variables which are defined as weighted

sums of the R&D inputs of the firms entering the ‘pool’. Distinguishing intra- and inter-industry R&D spillovers, the corresponding spillover pool variables for a firm i located in industry $S(i)$ can be written as

$$\text{INTRA}_i = \sum_{j \in S(i)} \varpi_{ij} \cdot R \& D_j \quad \text{and} \quad \text{INTER}_i = \sum_{j \notin S(i)} \varpi_{ij} \cdot R \& D_j, \quad (33)$$

where $j \neq i$ indicates the firms entering the respective pool.¹¹ The weights ϖ_{ij} should capture the likelihood that knowledge is disseminated between the firms i and j . There are numerous suggestions in the empirical literature on R&D spillovers for the specification of these weights: Jaffe (1986) uses the correlation between the two vectors of patent applications in different patent classes of the firms i and j . Inkmann and Pohlmeier (1995) extend this approach to the Euclidean distance of a large number of characteristics describing the technological distance between firms and industries.

Here, a new concept is introduced which rests on the firm’s subjective evaluation (π_i, π_j) of the probability that innovations are imitated. If both firms i and j claim that innovations are likely to be imitated then the leakage of innovative knowledge must be high or, in other words, the magnitude of R&D spillovers must be large. The subjective evaluation of the diffusion of innovative knowledge (π_i, π_j) is measured on scales from 1 (very low) to 5 (very high). Therefore, an ad hoc specification of the weight ϖ_{ij} which should capture the likelihood of bilateral knowledge dissemination can be defined as

$$\varpi_{ij} = (\pi_i + \pi_j - 1) / 10 \in \{0.1, \dots, 0.9\}. \quad (34)$$

Using these weights, divided by the number of firms entering the respective R&D spillover pool, and the R&D intensity of firm j in place of the R&D variable in (33), measures of intra- and inter-industry knowledge flows are obtained which serve as approximations of β and δ . The firms are aggregated into 13 different sectors for the construction of the pool variables which are shown in Table 3 below.

Kaiser (1999) performs plausibility checks for a number of R&D spillover variables using data on German manufacturing and service firms. He also considers the spillover pool variables (33) in combination with the weights defined in (34). From the set of six empirical

¹¹ An inherent problem of the methodology is that only firms in the sample enter the spillover pool while the population counterparts are the variables of interests.

R&D spillover variables included in his comparison, Kaiser recommends using either the one introduced in (33)/(34) or the one suggested by Jaffe (1986) while the other four variables may lead to counterintuitive results.

Table 3.
Descriptive Statistics (n = 1758)

Variable	Mean	Std. Dev.	Minimum	Maximum
R&D participation	0.6894	0.4629	0.0000	1.0000
R&D intensity	0.0297	0.0575	0.0000	0.5357
Intra-industry R&D spillovers ($\cdot 10$)	0.1318	0.0865	0.0047	0.4322
Inter-industry R&D spillovers ($\cdot 10$)	0.1298	0.0401	0.0722	0.2089
Horizontal R&D cooperation	0.0484	0.2146	0.0016	1.0000
Vertical R&D cooperation	0.1940	0.3955	0.0000	1.0000
Increasing demand expected	0.0518	0.2216	0.0000	1.0000
Number of employees ($\cdot 10^{-5}$)	0.1132	0.6936	0.0001	17.2447
Firm located in East Germany	0.3265	0.4691	0.0000	1.0000
Sector: mining, energy	0.0199	0.1397	0.0000	1.0000
Sector: food, textiles	0.0819	0.2743	0.0000	1.0000
Sector: wood, paper, printing	0.0830	0.2760	0.0000	1.0000
Sector: chemical products	0.0791	0.2699	0.0000	1.0000
Sector: rubber, plastics	0.0705	0.2561	0.0000	1.0000
Sector: mineral products	0.0336	0.1801	0.0000	1.0000
Sector: basic metals	0.0319	0.1757	0.0000	1.0000
Sector: metal products	0.1069	0.3091	0.0000	1.0000
Sector: machinery	0.2230	0.4164	0.0000	1.0000
Sector: electrical machinery	0.0933	0.2909	0.0000	1.0000
Sector: instruments	0.0745	0.2627	0.0000	1.0000
Sector: motor vehicles	0.0614	0.2402	0.0000	1.0000
Sector: construction	0.0410	0.1982	0.0000	1.0000

Source: Mannheim Innovation Panel (MIP), first wave 1993.

In order to make statements about the impact of the two spillover variables in the different R&D cooperation scenarios in accordance with (31) and (32), the R&D intensity equation contains interactions of the two spillover variables and the two cooperation dummies. Demand effects (described by the parameter Z in the theoretical model) are captured by a

dummy variable which indicates an expected increasing demand for the three years following the interview. Table 3 summarizes descriptive statistics of the estimation data.

The econometric specification accounts for the large fraction of firms reporting a zero R&D intensity by using a selection equation as proposed, e.g., by Heckman (1979). The well-known two-step estimator of Heckman's selectivity model is implemented in terms of a Generalized Method of Moments (GMM) approach as suggested by Newey (1984) which automatically generates a consistent estimate of the asymptotic variance-covariance matrix of the parameter estimates. The moment functions for this GMM approach are given by Newey and McFadden (1994, p. 2177). The specification of the selectivity model recently suggested by Newey (1999) is considered as an alternative to Heckman's specification. Newey's specification can also be estimated by the GMM approach to Heckman's two-step estimator with the only difference that the nonlinear correction term (the inverse of Mill's ratio) is replaced with the linear index of the selection equation. For identification reasons the linear index has to contain at least one regressor which is not included among the set of explanatory variables of the equation of interest. Such a linear correction term was proposed by Olsen (1980) who assumes an uniform distribution for the error term in the selection equation. Contrary to Heckman's specification, Olsen's specification of the selectivity model yields consistent slope coefficient estimates despite misspecification of the error term distribution under conditions derived by Newey. In addition to these selection models, ordinary least squares (OLS) estimates are presented for the selected sample of firms reporting a positive R&D intensity because the selectivity correction term appears insignificant in one of the two selection models (Olsen specification).

The size of the firm measured by the number of employees and an indicator for a location in the Eastern part of Germany (former GDR) are used as additional regressors in the R&D participation equation. The estimation results for the selection equation are not presented but can be summarized as follows. A firm located in the Eastern part of Germany is less likely to participate in R&D than a Western firm and larger firms are more likely to engage in R&D than smaller firms. The 12 sector dummies turn out jointly significant while the demand indicator turns out insignificant. Intra-industry R&D spillovers significantly reduce the probability of observing a firm participating in R&D while inter-industry R&D spillovers work in the opposite direction.

Table 4.
Estimation Results for the R&D Intensity Equation

Regressor	Heckman		Newey-Olsen		OLS	
	estimate	t-value	estimate	t-value	estimate	t-value
Intercept	0.0415	3.89	0.0610	6.52	0.0608	6.51
Increasing demand expected	0.0393	3.20	0.0401	3.35	0.0402	3.35
Horizontal R&D cooperation	0.0513	1.66	0.0408	1.32	0.0404	1.32
Vertical R&D cooperation	0.0026	0.16	-0.0071	-0.44	-0.0073	-0.46
Intra-industry R&D spillovers	-0.3885	-3.74	-0.2809	-3.11	-0.2799	-3.10
· Horizontal R&D cooperation	-0.0239	-0.40	-0.0208	-0.35	-0.0213	-0.36
· Vertical R&D cooperation	0.0047	0.11	0.0300	0.67	0.0300	0.67
Inter-industry R&D spillovers	0.3566	3.31	0.2000	2.31	0.1986	2.31
· Horizontal R&D cooperation	-0.2960	-1.60	-0.2463	-1.35	-0.2445	-1.35
· Vertical R&D cooperation	0.0126	0.12	0.0280	0.26	0.0290	0.27
Selectivity correction term	0.0495	3.22	-0.0002	-0.36	---	---
<i>Tests of joint significance</i>	χ^2 (df)	p-value	χ^2 (df)	p-value	χ^2 (df)	p-value
Slope parameters: (df = 22)	134.00	0.00	231.16	0.00	225.55	0.00
Sector dummies: (df = 12)	36.04	0.00	37.69	0.00	37.76	0.00

Note: The data source is the first wave of the Mannheim Innovation Panel (MIP), 1993. The columns labeled Heckman and Newey-Olsen contain GMM estimates of the selectivity models suggested by these authors. The OLS estimates are computed on the sample of firms reporting a positive R&D intensity using the heteroskedasticity-consistent estimate of the variance-covariance matrix suggested by White (1980).

Table 4 contains the estimation results for the R&D intensity equation which includes in addition a set of 12 sector dummies for which no results are presented except for the Wald statistic indicating the joint significance of these variables in all three specifications. The estimation results are similar for all three estimators. The GMM estimates for the Newey-Olsen selection model are very close to the OLS estimates. The demand indicator turns out positive significant in keeping with the theoretical impact of the parameter Z . Intra-industry R&D spillovers have a strong negative impact on the firms' R&D intensities while inter-industry R&D spillovers significantly encourage R&D efforts. Both results correspond to the general sign pattern derived from the theoretical model in (31) and (32). However, the predicted positive effect of intra-industry R&D spillovers on the R&D intensities of firms engaged in a horizontal R&D cooperation is not found. The dummy variables indicating a horizontal or vertical R&D cooperation as well as the interactions of these dummies with the R&D spillover variables turn out insignificant which prohibits any further interpretation. They remain

insignificant in more parsimonious specifications of the R&D intensity equation which include only one of the two cooperation forms or exclude the cooperation specific shift parameters.

6. Conclusions

This paper has introduced an extension of the oligopoly models suggested by D'Aspremont and Jacquemin (1988) and Steurs (1995) in order to explain both horizontal and vertical R&D cooperation between firms in the presence of intra- and inter-industry R&D spillovers. The model is a first attempt to incorporate the possibility of vertical R&D cooperation between upstream and downstream firms into the usual two-stage oligopoly models used to analyze horizontal R&D cooperation between firms operating on the same product market. For this purpose the usual second stage Cournot game is replaced with the successive oligopoly structure considered by Greenhut and Ohta (1979) which describes two vertically related industries and provides an endogenous determination of the price of the intermediate good. Firms in both industries invest in R&D in order to reduce their production costs. Distinguishing R&D competition and horizontal and vertical R&D cooperation between firms it turns out that vertical R&D cooperation usually maximizes the profits of the participating firms. Hence, the theoretical framework can explain vertical R&D agreements which clearly outnumber horizontal R&D agreements in practice. An empirical investigation of the impact of R&D spillovers on a firms' R&D intensity confirms the respective theoretically predicted negative and positive signs of intra- and inter-industry spillovers for the average firm but can not reveal the positive impact of intra-industry spillovers on the R&D intensity of firms engaged in a horizontal R&D cooperation.

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