Literature review: R&D cooperation in oligopoly with spillovers: An experimental economics approach

Suetens, S.

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Literature Review

R&D cooperation in oligopoly with spillovers: an experimental economics approach

Sigrid Suetens

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Contents

Introduction

Since decades, economists and policy makers recognise that the market provides too little incentives for firms to invest in research and development (R&D). Imperfect appropriability, uncertain outcomes and large sunk set-up costs are examples of factors that characterise R&D activities and drive a wedge between private and social benefits of R&D, and thus between private and social incentives to invest in R&D. One of the instruments that economists and policy makers have devised and used to tighten this gap, next to e.g. the patent system and subsidy policy, is the stimulation of formation of research joint ventures (RJVs) or other cooperative agreements related to R&D between otherwise competing firms. Indeed, anti-trust legislation of Western countries has provided an exception for such agreements given the potential social benefits.

In the industrial organisation (IO) literature much attention has been paid to the identification of circumstances under which R&D cooperation is actually welfare-improving compared to R&D competition and firms have incentives to enter cooperative agreements. It is e.g. generally accepted that one of the important conditions for cooperation to be welfare-enhancing is the existence of important knowledge spillovers between firms. This and other conclusions are made on the basis of relatively simple game-theoretic models of firms in oligopoly. Empirical and especially experimental tests of assumptions and/or predictions of the theoretical models are still exceptions, although catching-up on this ground has been very recently set in.

The main aim of this paper is to give the reader an idea of the large gap between the overwhelming theoretical IO literature on the topic of R&D cooperation and spillovers and the scarce empirical and experimental evidence motivated by this theory. Furthermore, suggestions for experimental research are put forward that extend or improve the related theory.

In chapter 1 an extensive overview of IO models that deal with R&D cooperation, after having situated these models in the more general theoretical R&D literature, is provided. Chapter 2 surveys empirical (non-experimental) analyses of R&D cooperation and spillovers motivated by theory, which mainly consist of econometric analyses. This chapter does not survey the more extensive empirical literature on R&D cooperation and RJV formation in general, but rather focuses on research related to the link with spillovers. In chapter 3 we give an overview of past laboratory research on R&D and related games. Here we adopt a broader approach since strategic interactions in experiments on R&D and R&D cooperation are much related to interactions in oligopoly experiments on quantity or price decisions and collusion, and to interactions in public goods/bads games.

Chapter 1

IO models of R&D cooperation

1.1 Introduction

In this chapter an overview is given of the mainstream theoretical IO literature on cooperative R&D behaviour of firms. In contrast to the transaction cost and strategic management literature, where scholars are traditionally more concerned about the internal organisation of firms[1], the (recent) IO literature concentrates on strategic interactions among firms mainly by applying a game-theoretic approach, and on the effects of firms' actions on variables as industrial structure, profit and welfare. A framework of multiple decision stages, with at least an R&D stage and a pricing or production stage, has become a widespread approach to model R&D decisions of firms and especially to examine issues of R&D cooperation.

Before turning to an overview of the cooperative R&D literature, we situate this type of models in the general IO literature on R&D in section 1.2. In sections 1.3 and 1.4 overviews are given of basic models with cost-reducing R&D and other types of R&D respectively. Section 1.5 gives an overview of important issues that are not (thoroughly) treated in the basic models. As is very common in this literature, it is mostly assumed that firms remain competitors in the final goods market, irrespective of whether they cooperate in R&D, or more general, how they behave before entering the final goods market. Section 1.6 gives an overview of the few papers that investigate the hypothesis—somewhat related to multimarket contact hypotheses[2]— that cooperation in the R&D market can enhance cooperation

[1]For overviews of the strategic management and transaction cost literature on R&D cooperation we refer to Hagedoorn et al. (2000), Alm and McKelvey (2000) and Calaghirou et al. (2003).

[2]We refer to Bernheim and Whinston (1990) and Matsushima (2001) for theoretical analyses of the link between multimarket contact and collusion in the final goods market.

in the final goods market. Section 1.7 concludes the chapter.

1.2 IO models of R&D: a general overview

Initially, oligopoly models of R&D were mainly set up to investigate Schumpeterian hypotheses that R&D and innovative activities are very much related to market structure and that innovative firms have some form of market power. As such, in the elder literature much attention has been paid to the relation between innovation(s) and (the evolution of) market structure. We distinguish two basic modeling approaches that have served for this and other analyses, i.e. tournament and non-tournament modeling.

A basic feature of tournament models is that the first firm that succeeds in innovating ends up to be the innovator which mostly comes down to winning a (patent) race. As such, in most of these models the *timing* of an innovation plays a central role in the sense that it is important to be the first to innovate (or to get a patent). Tournament models have been mainly but not solely used to investigate the above mentioned issues of market structure and market power. Gradually, as the literature began to focus more on R&D cooperation, especially after the publication of the paper of d'Aspremont and Jacquemin (1988), non-tournament models were more and more turned to.

Indeed, R&D cooperation is mostly dealt with in the context of a non-tournament model where firms are not engaged in a race but can all succeed at the same time in 'producing innovations'. A tournament setting may be associated with the existence of only one R&D path for firms to finally end up with an innovation while in a non-tournament setting several R&D paths, that are either closely related or not, may drive a firm towards innovating.

In what follows we present an overview of non-cooperative R&D models and distinguish between tournament and non-tournament settings without claiming that this is the ultimate way of structuring the extended strand of literature[3].

1.2.1 Tournament models

Among tournament models with timing we find deterministic races, where a deterministic relationship between R&D investment and the time needed to produce a practically relevant innovation is assumed, and stochastic races,

[3]Another option would be to add a category with 'grey zone' models that contain characteristics of both tournament and non-tournament settings.

where the relationship is stochastic[4]. In a deterministic race, the firm with the largest R&D investment today wins the race.

The very first contributions that contain equilibrium models based on single-stage stochastic patent races are Loury (1979), Lee and Wilde (1980) and Dasgupta and Stiglitz (1980b)[5]. Typically, the probability of winning the race depends on the R&D investment of a firm at a certain point in time. The model of Loury (1979) has fixed R&D costs while Lee and Wilde (1980) assume that part of R&D costs is variable and dropped as soon as a successful innovation is implemented. This difference in assumptions on costs of R&D investment yields opposing conclusions regarding the effect of rivalry in the product market on profit-maximising R&D expenditures. If R&D investment mainly consists of fixed (variable) costs, rivalry in the product market would reduce (enhance) R&D. Dasgupta and Stiglitz (1980b) provide an analysis based on a deterministic race.

The stochastic as well as the deterministic models predict that firms overinvest in R&D compared to what is socially optimal, given a fixed market structure. Welfare analyses suggest that, when entry to the market is not costless, perfect competition is not the socially optimal market structure but rather some form of imperfect competition.

A tournament setting is not necessarily based on issues of timing of innovation but can naturally result from other model characteristics. E.g. in Futia (1980) and Rogerson (1982), the innovator is randomly chosen with the probability of becoming the innovator depending on the amount of R&D undertaken. Overinvestment in R&D is also predicted by these models. Furthermore, Sah and Stiglitz (1987) posit a stochastic relationship between R&D effort and *final innovations* (instead of *becoming the innovator*). Firms are allowed to engage in more than one R&D project and the market is characterised by Bertrand competition. The model is of a tournament kind since a firm only gets a rent if she is the only successful innovator, as all profits are 'Bertrand-competed' away when several firms turn out to be successful. The model predicts that many asymmetric Nash equilibria exist and that firms' R&D expenditures are unaffected by market structure. Another result that contrasts with findings of models with timing is that market expenditures on R&D are less than socially optimal.

The racing models with timing have been extended or adjusted on several

[4]For an extended overview of the literature on timing of innovation we refer to Reinganum (1989). She uses the terms "deterministic auction models" and "stochastic racing models".

[5]These contributions should be seen as extensions of models examining the effect of exogenous market structure on innovation. For overviews we refer to Kamien and Schwartz (1975) and Loury (1979).

grounds. First, there is the issue of appropriability. In the original contributions it was assumed that patent protection was complete while 'newer' models allow for imperfect patent protection. In Stewart (1983) a unique value of a winner's share in total industry profit exists that maximises profits and that leads to a choice of R&D strategies by the other firms similar to strategies cooperating firms would choose. Increased competition would lead to a fall in the firm's R&D investment as long as spillovers are too high and the winning firm thus receives a lower profit from it's innovation than the profit she would receive under the optimising share parameter. Mortensen (1982) comes to a similar conclusion in a tournament framework without timing. The main conclusion of Reinganum (1982), who assumes that the firms that are not the first to innovate still receive a positive payoff, is that when patent protection is ineffective, firms do not have incentives to invest in R&D. Clearly, when taking into account issues of appropriability, overinvestment in R&D does not occur.

Instead of assuming symmetry among all firms in an industry, some models have started from a market with one incumbent firm and several potential entrants. The main interest now goes to firms' incentives to engage in innovative activities rather then to how market structure and innovative activities are related. Reinganum (1983) and Reinganum (1985) provide models with one firm and one possible innovation and several firms and a sequence of innovations respectively. The latter model is a multi-stage model where all profits accrue to an innovator only as long as nothing new is invented. As elaborated on by Reinganum (1989), this 'incumbent-versus-challenger(s)' set-up yields differences in R&D incentives between both types of firms. The main finding is that in a Nash equilibrium, the incumbent monopolist invests less in R&D than the outside 'challengers' as he anticipates future (drastic) innovations of the challenger(s) that reduce the present value of his profits. This is in contrast to findings from deterministic race models, such as e.g. Gilbert and Newberry (1982), where the incumbent comes out to be the largest R&D spender and thus persists as a monopolist[6].

Another application of asymmetries among firms is to let the probability of winning the patent race depend on accumulated knowledge by interpreting an R&D project as a multi-stage game where the winner is the first firm that completes all stages. Examples of models where firms proceed to further stages in a deterministic way are Fudenberg et al. (1983)[7] and Harris and

[6]According to Reinganum (1989) both type of models are not mutually exclusive. Stochastic races would be better suited to model uncertain basic research, while deterministic races more apply to development and new product introduction.

[7]In Grishagin et al. (2001), a patent race similar to Fudenberg et al. (1983), is considered where firms do not know their relative position during the race.

Vickers (1985). In Grossman and Shapiro (1987) the time before entering a following stage is stochastic while in Harris and Vickers (1987) there is a stochastic relationship between the amount of R&D and winning a stage. A general result is that a typical response for a firm having success in the first stage(s) is an increase in R&D effort of the leading firm and a decrease for the lagging firm. If firms' accumulated knowledge is sufficiently close, i.e. if the firms remain tied, they will choose to invest in R&D at a high rate. Results of the deterministic models are even stronger since if one firm is only slightly ahead, the other simply drops out of the race.

A recent further improvement by Doraszelski (2003) to capture knowledge accumulation in a dynamic R&D race yielded other conclusions. In his model, the distribution of success times depends on current R&D expenditures and the accumulated (depreciated) knowledge stock. Simulations yield that pure knowledge gathering dominates strategic considerations as R&D incentives decline with an increase in the knowledge stock. Consequently, the firm that lags behind, and thus has a relatively low knowledge stock, may invest more in R&D than the leader who has a large knowledge stock. As such, lagging firms not necessarily drop out of the race but may be engaged in catching-up.

1.2.2 Non-tournament models

As already mentioned, most theoretical contributions on R&D cooperation are of a non-tournament kind where several firms can have successful R&D projects at the same time. On the other hand, (recent) non-tournament R&D models also concentrate mostly on comparing modes where firms cooperate in R&D with more competitive modes. The emergence of (predominantly non-tournament) models on R&D cooperation is closely connected to the general recognition of knowledge spillovers. Due to public good characteristics of R&D, firms cannot always reap all benefits of their R&D. R&D cooperation would then be a natural candidate to solve this problem by internalising the spillovers.

As mentioned before, in the beginning of the eighties much attention went to the relation between innovation and market structure. On the basis of Dasgupta and Stiglitz (1980a), where symmetric firms choose R&D and output simultaneously, similar conclusions as in 1.2.1 regarding some form of imperfect competition being the socially optimal market structure are made. Brander and Spencer (1983) argued that in a simultaneous single-stage game with cost-reducing R&D an implicit assumption is that the exclusive aim of R&D investment is to reduce marginal production cost. They raised the issue that firms most likely have also more strategic considerations, such as gaining market share, and take decisions that are to be made in the product market into account when they invest in R&D. If this is the case, R&D should be modelled in a two-stage game. In a first stage, the R&D decision is simultaneously made by all firms, and in a second stage, output or price levels are chosen. If it is assumed that firms are rational, the solution concept of the game is SPN (SPN) equilibrium and the appropriate solution method is backward induction. This approach is mostly used in non-tournament models of R&D.

Within this strategic setting one can also distinguish between deterministic and stochastic models. In deterministic models R&D investment automatically yields an innovation while in stochastic models (see e.g. Reynolds and Isaac, 1992; Choi, 1993; Katsoulacos and Ulph, 1998) a stochastic relation is assumed between R&D effort and outcome[8]. Decisions in the R&D stage affect either unit production cost (see e.g. Katz, 1986; d'Aspremont and Jacquemin, 1988; Kamien et al., 1992) or product quality (Motta, 1992) and are usually characterised by knowledge spillovers that result in costless advantages for the competitor.

The analysis of Spence (1984) is one of the first to formally take into account the issues of knowledge spillovers and R&D subsidies in a strategic R&D model with n firms. In his paper unit production cost is a declining function of the knowledge stock of a firm, which grows with current R&D expenditures and spilt over R&D expenditures of other firms. He does not explicitly model the product market but assumes that at any point in time an equilibrium in quantities exists. It is found that R&D incentives decrease as appropriability is lower (or spillovers higher) and as concentration declines (given low appropriability). Therefore, according to the author, government should subsidise R&D, especially when spillovers are high. Moreover, welfare is highest in markets with high spillovers and appropriate subsidies. Further, it is also suggested that cooperative R&D may be suitable to raise welfare.

A non-strategic model where the effects of spillovers are included is Levin and Reiss (1988). Firms simultaneously decide on cost-reducing process and quality-enhancing product R&D and on production quantity. The main conclusion is that when taking into account spillovers from process R&D to product R&D or *vice versa*, higher spillovers not necessarily reduce R&D incentives.

Most strategic R&D models specifically deal with R&D cooperation and

[8]In this context we refer to the earlier mentioned 'grey zone'. Stochastic non-tournament models have some characteristics of tournament models, since they allow for the possibility of only one firm ending up with an innovation. Sah and Stiglitz (1987), though, is an example of a model with a stochastic relation between R&D and innovation that can be considered as a tournament model because of the way the product market is modelled (see 1.2.1).

these models are discussed in the following sections. Non-cooperative models in a non-tournament setting usually focus on asymmetric situations where one firm has an advantage over the other. In Poyago-Theotoky (1996) e.g., firms in duopoly that have different initial unit production costs, simultaneously make R&D decisions in a first stage and quantity decisions in a second stage. She finds that depending on the choice of cost function the low- or high-cost firm spends more on R&D. When an additive cost function is used the low-cost firm spends more due to an incentive effect. With a multiplicative cost function the high-cost firm spends more because of the emergence of an effectiveness effect.

Some authors have also looked at another form of asymmetry, namely a sequential equilibrium where firms start with leader/follower roles that result e.g. from a pre-development race. In Bondt et al. (1992) symmetric firms that sell differentiated goods play a sequential game while in De Bondt and Henriques (1995) and Amir et al. (2000) firms start with different initial unit production costs and/or spillovers. De Bondt and Henriques (1995) find that the firm that is good (bad) at absorbing information[9] ends up to be the leader (follower) of the R&D game. This leading firm is not necessarily the one that started with lower production costs or higher R&D efficiency. A similar result is found in Amir et al. (2000). Moreover, depending on the ratios of spillover rate to demand cross-slope, the endogenous emerging sequential solution yields higher profits for both firms and higher welfare than the simultaneous solution.

Joshi and Vonortas (1996) view the R&D process as a two-stage process where technological knowledge is generated from basic research through a knowledge production function in a first stage and this knowledge is transformed into unit cost reductions in a second stage[10]. Different parameterisations of the knowledge production function and the unit cost function are compared and the authors conclude that the reaction of optimal R&D expenditures to changes in initial knowledge stock and own and rival's spillovers rates depends on (a) the elasticity of output with respect to R&D; (b) the elasticity of knowledge with respect to R&D and (c) the degree of convexity of the unit cost function.

[9] A higher absorptive capacity implies that incoming spillovers are higher than outgoing spillovers.

[10] See also 1.5.6.

1.3 Basic models of R&D cooperation with cost-reducing R&D

In what is by far the largest part of the literature on cooperative R&D games, R&D is defined as cost-reducing. This is often interpreted as R&D being process R&D. In most of these models, knowledge spillovers enter the model and effective R&D of a firm is defined as the sum of its own R&D and R&D spilled over from other firms in the industry, where the spilled over part is never larger than the R&D carried out by the firm itself[11].

As mentioned before, most models are two-stage models where perfectly informed firms simultaneously decide how much to invest in R&D in a first stage and on prices or production quantities in a second stage. In a first stage firms either play a non-cooperative R&D game or a cooperative R&D game. In the cooperative game it is standard to assume that the firms can credibly commit to the cooperative R&D level which is the level of R&D that maximises total industry profit[12]. The equilibrium concept of the non-cooperative game is the SPN equilibrium.

In general, the profit function of firm i in an industry with n firms engaged in Cournot competition is defined as follows

$$\pi_i = p_i q_i - c_i(X_i)q_i - g_i(x_i),$$

where p_i is the inverse demand function of firm i[13], $c_i(X_i)$ the unit cost function with $X_i = x_i + \beta \sum_{j \neq i}^{n} x_j$ representing effective R&D of firm i and $g_i(x_i)$ the R&D cost function with x_i representing R&D investment of firm i. β is the spillover parameter.

The model is solved by backward induction. In the second stage π_i is maximized with respect to q_i for all i, which yields a first-stage profit function in terms of the R&D investment of firm i and the other firms in the industry. In a scenario without R&D cooperation, the first-stage profit function of firm i is maximized with respect to x_i, yielding a symmetric equilibrium prediction for x_i. In a scenario with R&D cooperation, on the other hand, total industry profit is maximized with respect to x_i, yielding a cooperative outcome for x_i which is usually assumed to be symmetric across the industry. Most of the literature focuses on comparisons between R&D predictions, welfare, industry profit, etc. in non-cooperative and cooperative R&D scenarios.

[11] As noted by Bondt (1996), the earliest formal oligopoly model with spillovers can be found in a paper of Ruff (1969).

[12] In Battaggion and Garella (2001) different scenarios of R&D cooperation are examined in a model with unverifiable R&D efforts.

[13] In the case of Bertrand (price) competition in the second stage, the demand function would be q_i.

A model that has received much attention in the game-theoretic R&D literature and has stimulated further research on the topic is in the paper of d'Aspremont and Jacquemin (1988, 1990)[14]. In the model the industry is a duopoly with Cournot-competing firms, homogenous goods and a linear demand function. Decision variables in the first stage are unit production cost reductions and spillovers are thus *output* spillovers. A quadratic R&D cost function is introduced as to guarantee diminishing returns to own R&D, although this does not guarantee that returns to *effective* R&D are also diminishing as shown in Amir (2000). As such, $c_i(X_i) = c - X_i$ and $g_i(x_i) = \delta\frac{x_i^2}{2}$. Findings are that R&D cooperation only enhances R&D investment and welfare when spillovers are large enough and that firms always underinvest in R&D compared to the welfare-maximising solution.

A two-stage model where the first-stage decision variable is R&D investment and spillovers are *input* spillovers is developed by Kamien et al. (1992)[15]. The industry consists of $n \geq 2$ firms that produce differentiated products and are either engaged in Cournot or Bertrand competition in the second stage. Demand is linear and unit cost consists of a constant part minus 'R&D production', where the R&D production function is concave in effective R&D. In their model, $c_i(X_i) = c - f_i(X_i)$ where $f_i(X_i)$ is twice differentiable and concave in X_i, $f_i(0) = 0$, $f_i(X_i) \leq c$ and $f_i'(X_i) > 0$, and $g_i(x_i) = x_i$. Four possible organisation types, i.e. R&D competition, R&D cartelisation, RJV (research joint venture) competition and RJV cartelisation are compared. The first mode, R&D competition, implies that each firm individually decides how much to invest in R&D as to maximise individual profit, while R&D cartelisation implies that firms coordinate their R&D activities in order to maximise the sum of their profits. In the case of RJV competition firms also operate individually and spillovers are complete, while the forming of RJV cartels implies coordination of firms' R&D decisions and complete spillovers. In other words, if firms form an RJV, they fully share information about their R&D activities. Findings are that RJV cartelisation is the most desirable type of organisation, as prices are lowest and technological improvement highest. On the other hand, RJV competition yields highest product prices. This means that only if firms form a cartel, they should be encouraged to coordinate their R&D activities and form an RJV.

In the same tradition Suzumura (1992) sets up a model with general demand and cost functions with firms producing a homogenous good and competing in quantities in the second stage. It is found that in the presence

[14]Henceforth AJ.

[15]Henceforth KMZ.

of large spillovers, there is always underinvestment in R&D compared to the socially optimal level. Cooperative R&D investment is closer to welfare-optimising R&D than non-cooperative investment though. In the absence of spillovers the level of R&D in the non-cooperative equilibrium may overshoot the socially optimal level, when the number of firms in the industry is relatively large and demand is concave.

A general finding of the above models is that when spillovers are small, i.e. below a certain threshold, R&D investment and social welfare are higher when firms choose their R&D non-cooperatively compared to when they choose their R&D as to maximise total industry profit. For spillover levels that are above the threshold the opposite is valid. In that case R&D investment and welfare are higher under R&D cooperation than under R&D competition. These conclusions are based on the assumption that firms compete in prices or quantities in the second stage. Collusion in both stages of the game yields lower welfare than R&D cooperation combined with price or quantity competition. These results are often interpreted as a rationale for government to allow and even stimulate the formation of RJVs in industries characterised by large knowledge spillovers. Furthermore, they suggest leniency in anti-trust policies towards R&D cooperation provided that the cooperation does not extend to the product market.

As established by Amir (2000), the AJ and KMZ models differ with respect to some key conclusions and policy descriptions. The AJ model seems to be of limited validity for large spillover levels as for these values industry R&D investment has increasing returns to scale, while individual R&D has decreasing returns. Equilibrium predictions of both models can be made equivalent by using a steeper cost function in the AJ model.

Yi (1996) adds that the range of spillover rates where R&D cooperation raises social welfare compared to R&D competition broadens, the higher the elasticity of the slope of the inverse demand function gets. In addition, Simpson and Vonortas (1994) argue that suboptimal investment in cost-reducing R&D under R&D competition is not only more likely the larger the degree of spillovers, but also the greater the convexity of the demand curve. They further find that when demand is concave, R&D cooperation with a single research lab always improves social welfare, while when demand is convex it only does when there are sufficient spillovers.

A further generalisation is found in Ziss (1994). His analysis is based on general demand and cost functions that satisfy conditions for a symmetric and unique equilibrium to exist in the product market (second stage). Ziss (1994) also allows for product differentiation and price as well as output competition in the product market. A thorough analysis of the strategic effects of R&D investment, referring to how second-stage actions (prices or quantities) are affected by R&D, is also provided in his paper. He finds that—due to a negative strategic effect—the existence of large spillovers in an industry does not guarantee that RJVs improve welfare compared to a situation where firms choose R&D non-cooperatively. The author also finds that the movement from a fully non-cooperative regime to price collusion (without R&D cooperation) can be welfare-improving for large spillovers.

1.4 Other models of R&D cooperation

The bulk of the literature on R&D cooperation is based on models with cost-reducing R&D activities or process R&D and only few have analysed R&D cooperation in the context of other models. We further distinguish between models where the R&D stage is a patent race and models where R&D improves product quality or enhances product differentiation.

1.4.1 Patent race

Some years ahead of the emergence of what has become the mainstream literature on knowledge spillovers and R&D cooperation, Reinganum (1981) examined the issues in a stochastic patent race framework. In her model, although perfect patent protection is assumed, imperfect appropriability is incorporated by allowing for knowledge spillovers between rivals in a similar way as in (later) non-tournament models. R&D cooperation also refers to joint profit maximisation. Conclusions on whether cooperation is socially beneficial are very similar to conclusions of non-tournament models. Without knowledge spillovers, innovation of competing rivals occurs on average sooner than innovation of cooperative firms while with complete knowledge spillovers, cooperating firms are the first to innovate. Consequently, the degree of spillovers is a critical value in determining under what R&D mode innovation occurs most rapidly. Similar conclusions are made by Miyagiwa and Ohno (2002) where the critical threshold relates to the *speed* of spillovers. More specifically, with slow (fast) spillovers, R&D cooperation lowers (increases) R&D investment.

Silipo (2001) introduces the possibility of R&D cooperation in the model of Fudenberg et al. (1983). He defines R&D cooperation as a situation where firms share costs and benefits (in this case a prize) of their research activities. It turns out that firms undertake an RJV if they have the same amount of accumulated knowledge in the beginning of the race. If the gap between a leader and a follower is too large, no RJVs are formed. Furthermore, cooperative agreements are broken up at the end of the race if competition is expected in the subsequent market, while they are not if a possibility to collude exists. As such, at the end of a race incentives to reduce costs are replaced by incentives to become a monopolist. As in the situation without spillovers in Reinganum (1981), cooperation tends to reduce the speed of innovation.

1.4.2 Product R&D

Motta (1992) was the first to present an analysis of R&D cooperation where R&D is aimed at improving the quality of a product. For this purpose, it is assumed that consumers incorporate product quality in their utility function, which yields non-linear (inverse) demand curves. Only *vertical* product differentiation is taken into account. By doing R&D, firms are able to increase the quality of their product above a minimum level. The model has three stages, in a first stage firms decide whether or not to enter the market, in a second stage they invest in R&D and in a third stage they choose outputs. Findings are very similar to the basic models of R&D cost reduction. R&D cooperation—where it is assumed that between cooperating firms spillovers are higher compared to when no cooperation occurs—enhances welfare compared to non-cooperative behaviour for spillover levels that exceed a certain threshold. An additional result is that when spillovers are not too high, under R&D competition only a finite number of firms enters the market, while under R&D cooperation more firms enter.

Poyago-Theotoky (1997) models product R&D in a different way and also takes *horizontal* product differentiation into account which yield other demand functions than in Motta (1992). It is further assumed that the market consists of two firms that are specialised in improving one out of two characteristics of the product and two firms that are specialised in the other characteristic. By doing R&D individually, firms can improve their product only in 'their' characteristic[16] and by forming an RJV, firms can improve their product in both characteristics and develop as such a "superproduct" which is sold at a common price. Innovation is an uncertain event and becomes more probable as investment in R&D increases. The main conclusion is that cooperation in R&D (that extends to the product market in a natural way) is welfare enhancing when the quality improvement of the resulting new product is high or when R&D is relatively inefficient and has high decreasing returns.

Examples of oligopoly models where R&D enhances product differentia-

[16]Note that this model has some characteristics of a tournament model, because only one patent is granted per characteristic of the product.

tion are Lambertini and Rossini (1998) and Cellini and Lambertini (2002). If all firms decide not to invest in R&D, products remain homogenous and the more firms invest, the more differentiated products become. In the former model, it is shown that firms may end up producing homogenous goods and that R&D incentives are higher under Bertrand competition than under Cournot competition. The main finding based on the latter, dynamic, model is that in the steady-state equilibrium R&D investment and thus also product differentiation are higher under R&D cooperation than under competition.

1.5 Important issues related to models of R&D cooperation

1.5.1 Information sharing

As argued in AJ and KMZ it is quite unlikely that the formation of cooperative R&D agreements is only restricted to joint profit maximisation and not related to the sharing of information. Obviously, we would expect that if firms make agreements on their R&D investment, more information will be shared than without an agreement. This section gives an overview of papers that deal with the topic of information sharing and endogenous spillovers.

We find two distinct ways of dealing with the issue of R&D cooperation with information sharing in the literature. The first is to keep the spillover exogenous and assume that as firms cooperate in R&D, the level of spillovers increases, compared to a situation without R&D cooperation (Kamien et al., 1992; Choi, 1993; Brod and Shivakumar, 1997; Miyagiwa and Ohno, 2002; Hinloopen, 2003). The second approach is to endogenise the spillover parameter and thus to treat the level of spillover or information sharing as a decision variable.

Brod and Shivakumar (1997) allow for product differentiation and $n \geq 2$ firms in the AJ model and assume that the spillover parameter becomes one under R&D cooperation. R&D cooperation in their model thus combines joint profit maximisation with respect to R&D and full information sharing. They find that cooperative R&D always yields more profit and is always preferred on welfare grounds. Miyagiwa and Ohno (2002) who make a similar assumption in a patent race framework find that information sharing does not always yield more profit (e.g. if there are many firms in the market), but is preferred on welfare grounds. Hinloopen (2003) finds that in a two-stage duopoly with homogenous goods based on Kamien et al. (1992), even if the pre-cooperative spillover level is small, R&D cooperation could be preferred on welfare-grounds, i.e. when cooperation yields high enough post-cooperative spillovers.

Let us turn to some examples of models where the spillover level is endogenous. Kultti and Takalo (1998), Katsoulacos and Ulph (1998), Poyago-Theotoky and Lambertini et al. (2004) simply introduce an additional stage in the basic duopoly model that follows the R&D stage and proceeds the production stage with Cournot competition. In Kultti and Takalo (1998) in the first, R&D, stage there are no spillovers and in the second stage firms have to decide on whether they would exchange their R&D results, yes or no. The finding is that firms have incentives to share information. Poyago-Theotoky and Lambertini et al. (2004) let firms decide on the height of the spillover after having made an R&D decision. The outcome is that under R&D competition no information will be disclosed while under R&D cooperation information is fully shared. Similar results are found in Amir et al. (2003) on the basis of a two-stage model—with possible exogenous spillovers—where cooperative firms take R&D and within-RJV information sharing decisions simultaneously in the first stage[17].

In a stochastic framework Katsoulacos and Ulph (1998) find that firms in the same industry will not disclose more information than the minimum level of already existing exogenous spillovers, while under R&D cooperation at least one firm will fully share information, provided that R&D of both firms is successful[18]. Information-sharing under R&D cooperation is not always maximal nor symmetric though due to anti-competitive reasons.

An additional stage that precedes the R&D decision stage has been added to a basic-two-stage model by Kamien and Zang (2000). Firms choose the extent of spillovers their R&D activities generate (outgoing spillovers) before deciding on R&D and at the same time allow for involuntary (exogenous) spillovers. They also assume that firms need some absorptive capacity, by doing R&D themselves, to be able to take advantage of knowledge flows from competitors (see also 1.5.6). Much related to previous results they find that if firms cooperate in R&D, they choose to fully share their knowledge. If R&D budgets are set non-cooperatively, firms choose to keep at least part of their knowledge private. Only when no exogenous spillovers exist, would they disclose all their knowledge. What the consequences are for welfare is not clear.

[17]They also leave out the assumption of *ex post* symmetry of R&D decisions of firms in an R&D cartel, but the consequences of this are discussed in the section 1.5.2.

[18]In complementary industries information-sharing with and without cooperation is identical and may be maximal even without R&D cooperation.

1.5.2 Asymmetry

There are two forms of asymmetries; *ex ante* asymmetries and *ex post* asymmetries. *Ex ante* symmetries are related to initial assumptions on the model's parameters, while *ex post* asymmetries refer to outcomes of a model which is not necessarily *ex ante* asymmetric. Within the literature on *ex ante* symmetries we make a further distinction between models where the asymmetries are related to production or R&D cost parameters and models that build on the assumption of asymmetric spillovers.

Röller et al. (1998) introduce the possibility of asymmetric initial unit costs in a duopoly model with allowance for complementary and substitutable products, where it is assumed that without (with) R&D cooperation there are no (complete) spillovers. They find that the higher cost firm always has an incentive to participate in an RJV, while the low cost firm only has an incentive when products are enough differentiated and when the cost asymmetry is not too large[19]. In Lukach and Plasmans (2000) asymmetry with respect to unit cost and R&D cost functions is introduced in the AJ model. It is assumed that the larger firm has a smaller unit production cost and a lower marginal R&D cost. An important result of their model is that in a welfare-maximising scenario, levels of R&D are asymmetric and that only the larger firm produces output, while both firms remain active in R&D. In general, conclusions on industry R&D, output and total welfare are similar to the original AJ findings.

Petit and Tolwinski (1999) consider asymmetries in initial unit costs and rates at which unit costs decline with accumulated R&D in a dynamic duopoly framework with general nonlinear demand and cost functions. When the assumption of *ex ante* symmetry is kept, conclusions regarding R&D and welfare of the dynamic model are similar to the ones reached in earlier models such as the AJ model. When asymmetries are introduced, the firm that starts with the high unit cost or has a lower innovation rate gets driven out of the market, unless there are knowledge spillovers that make the firm reduce its cost for free. Furthermore, incentives to form RJVs can be very low in asymmetric markets while for consumer surplus the existence of technology sharing and the formation of RJVs is advantageous.

In Amir and Wooders (1999, 2000) the effects of one-way spillovers on equilibrium predictions for symmetric firms are examined. The set-up of these models is the same as the basic set-up except in the way R&D spillovers are modeled. R&D spillovers only flow from the more R&D active to the other firm in an "all-or-nothing probabilistic fashion". The model only yields

[19] The authors do an empirical test of the model's predictions in the same paper. We refer to the second chapter for details on this.

asymmetric R&D equilibrium levels whereby the innovator—i.e. the firm that does the most R&D—sometimes conducts more R&D than an RJV cartel would. Under these conditions profit under R&D competition is also higher than in the RJV cartel. Spillovers in Lambertini et al. (2004) are not assumed to be one-way but simply asymmetric. Another source of asymmetry in both papers is related to a firm being a leader. In Lambertini et al. (2004) it is assumed that one firm takes a Stackelberg leader position in the final goods market. In the case of exogenous spillovers, if the outgoing spillover of the leader is sufficiently low, the leader invests more in R&D than the follower. With endogenous spillovers, the leader invests less and the follower more than under the Nash equilibrium. Welfare implications are not discussed in their paper but they do find larger industry R&D effort under the Nash equilibrium than under the Stackelberg equilibrium when spillovers are endogenous.

Finally, we look at *ex post* asymmetry. First, the issue of *ex post* asymmetry arises in the context of stability of R&D equilibrium predictions. As argued in Henriques (1990) and Amir and Wooders (1998), the symmetric equilibrium under individual profit maximisation with respect to R&D, assuming competition in the product market, is unstable for small spillover values and specific choices of the model's parameters. In this situation, the stable equilibrium predictions can be corner solutions where only one of the two firms invests in R&D. Under certain conditions—i.e. initial unit costs being high compared to demand—even total industry profit that corresponds to these asymmetric non-cooperative solutions is larger than under R&D cooperation with full information sharing (Amir and Wooders, 1998).

Assuming that equilibrium predictions are stable, it has been shown in amongst others Amir et al. (2003) that the R&D equilibrium decisions in the first-stage of a non-cooperative R&D game with product market competition in the second stage are unique and symmetric. So, not only are firms *ex ante* symmetric (by assumption) but the resulting *ex post* outcome is also symmetry. In the cooperative game this ex post symmetry is not guaranteed as argued in Katsoulacos and Ulph (1998) and more formally proved in Salant and Shaffer (1998)[20]. Katsoulacos and Ulph (1998) find in a model that includes uncertainty about R&D results that an RJV may close a lab for anti-competitive reasons, i.e. to avoid competitive pressures that arise when both firms discover.

Salant and Shaffer (1998) use the AJ model to prove that members of an RJV can gain higher profits by making unequal R&D investments compared to when they would invest the same amount in R&D. An important impli-

[20]In Salant and Shaffer (1999) this issue is discussed in a more general two-stage Cournot framework where first-stage actions affect marginal costs.

cation of their analysis is that in the specific framework they use it cannot be concluded that welfare is reduced by allowing firms to cooperate in R&D when spillovers are sufficiently small. For certain parameter combinations, the decline in consumer surplus is more than compensated by a rise in total industry profit[21].

Finally, *ex post* asymmetries can also appear if the deterministic R&D process is replaced by a stochastic one (as e.g. in Hauenschild, 2003). If e.g. only one firm succeeds in innovating, unit cost reductions and the resulting product market outcomes naturally are asymmetric across firms, given that they do not cooperate in R&D.

1.5.3 Uncertainty

Models of R&D cooperation are often based on the assumption of a deterministic relation between R&D investment and production cost reductions and/or product innovation, while it is generally acknowledged that R&D and in particular basic research is a highly uncertain activity. Naturally, when incorporating uncertainty about R&D results in models of R&D cooperation, it cannot be avoided that the resulting game has tournament features. Indeed, when the success of R&D is uncertain, it is not sure that all firms succeed in ending up with innovations such as e.g. production cost reductions or product improvements[22].

Abstracting from spillovers that may generate incentives to cooperate in R&D, Marjit (1991) deals with uncertainty in a duopoly model of cost-reducing R&D. He finds that cooperative R&D tends to be profitable when the probability of success of R&D is either very high or very low, i.e. when both firms are not likely to gain a monopoly position by succeeding alone in the R&D project.

In Choi (1993), Combs (1993) and Katsoulacos and Ulph (1998) the probability of success of R&D is higher the more a firm invests in R&D. Choi (1993) assumes that under a cooperative R&D agreement, both firms (a duopoly is considered) have access to any innovation that is made and that the probabilities of success remain independent among the members. He further assumes that total industry profit decreases as the level of spillovers increases due to more intense product market competition. Findings are

[21] In a more general framework Dakhlia et al. (2003) identify conditions under which cooperative asymmetric R&D decisions and the resulting increase in industry concentration are welfare-reducing.

[22] For examples of models of R&D cooperation that incorporate uncertainty regarding the *date* of innovation (stochastic patent races) we refer to section 1.4.1.

that under perfect monitoring[23] profits from cooperative R&D are higher compared to the non-cooperative mode when the natural spillover level is 'high enough', while they may be higher or lower for low spillovers. Conclusions regarding the gap between private and social incentives to cooperate in R&D are very similar to earlier findings.

Finally, Hauenschild (2003) compares stochastic versions of the AJ and the KMZ model with the original deterministic versions (see also section 1.5.4).

1.5.4 R&D input versus R&D output

As pointed out by Amir (2000) and suggested on the basis of empirical evidence (see chapter 2), it is important to distinguish between input (as in KMZ) and output spillovers (as in AJ) and as such between R&D input and R&D output as decision variables. Input spillovers are more related to the free access to e.g. basic research results in an industry, scientific publications or general information on what research is going on in the industry. Martin (2002) provides the example of the pharmaceutical industry, where firms' scientists generally have "... a quite accurate idea of the nature of research conducted by their competitors ...". Output spillovers rather refer to the appropriability of new technologies that result from research, which can be e.g. patented.

For the same level of spillovers, effective total cost reductions are always higher in the AJ model with output spillovers compared to the KMZ model with input spillovers when only symmetric solutions are considered, unless there are no spillovers. This is not surprising because in the AJ model (with output spillovers), only own R&D investment has decreasing returns and R&D output of the other firm is additively available.

Based on a comparison by Hauenschild (2003) of stochastic versions of the AJ and KMZ models with homogenous goods and Cournot competition, where R&D yields a unit cost reduction with a probability lower than 1, this relation is somewhat modified. Indeed, with output spillovers expected cost reductions tend to be reduced by the uncertainty, while increased with input spillovers. As such, for some parameter combinations, effective total cost reductions with input spillovers are expected to be higher than with output spillovers.

Martin (2002) incorporates input and output spillovers in a stochastic patent race model with two firms. It is assumed that under R&D cooperation the two firms carry out R&D independently and R&D input spillovers are

[23] Each firm can observe the other's R&D investment and outcome.

complete. Findings are that R&D cooperation always yields higher total welfare, but not higher profit if either natural input spillovers are high and/or output spillovers are low (high appropriability).

Another way of distinguishing between input and output spillovers is to split up the R&D process into two stages (see e.g. Beath et al., 1998); one stage that maps R&D input into R&D output and one stage that maps R&D output into unit cost reductions. This approach not only makes it possible to distinguish between input and output spillovers but also between different characteristics of the functions that map R&D input into output and R&D output into cost reductions. Beath et al. (1998) show that it matters at which stage diminishing returns of R&D set as to predict how many R&D labs an RJV would operate.

1.5.5 Complementarity of R&D

It is clear that in the models of R&D cooperation overviewed so far, the spillover parameter (often referred to as β) makes it possible for a firm to reduce unit production costs or enhance product quality without doing R&D itself, i.e. by the R&D investment of other firms. Moreover, the standard assumption is that R&D input (in the case of KMZ-type models) or R&D output (in the case of AJ-type models) of other firms in the same market is additive to a firm's own R&D input or output[24]. The 'degree' of additivity depends on the height of the (exogenous) spillover β. When $\beta = 1$ e.g., other's R&D is perfectly additive to own R&D.

The height of the spillover parameter is also related to the strategic properties of R&D decisions. It is standard in the duopoly literature that with 'low' spillovers, R&D decisions are strategic substitutes implying that the best response of a firm to an increase in the other's R&D investment, is to decrease it's own R&D investment. Under these conditions, R&D investment has negative externalities and R&D cooperation has an R&D-effort-saving effect in KMZ-type models and reduces R&D output (unit cost reduction) in AJ-type models. This may be because firms follow closely related R&D paths and at least partly duplicate each other's R&D. With 'high' spillovers, on the other hand, R&D decisionsare strategic complements and have positive externalities such that R&D cooperation enhances R&D investment or R&D output in KMZ-type and AJ-type models respectively. In this case, one could argue that R&D paths are rather complements.

In any case, the spillover parameter in standard models is highly related

[24]For an extensive comparison of additivity in AJ-type and KMZ-type models, we refer to Hinloopen (2003).

to complementarity properties of R&D investment. Beath et al. (1998) e.g. make different assumptions on the height of the spillover parameter depending on whether firms follow a single research path or complementary research paths. Findings are that only one lab will be operated with a single research path and one or two with a complementary research path, depending on the stage of the R&D process at which diminishing returns set in.

Examples where spillovers and properties of R&D related to the degree of complementarity[25] are formally disentangled are Katsoulacos and Ulph (1998) and Anbarci et al. (2002).

While the standard assumption in AJ- and KMZ-type models is that under R&D cooperation both firms in duopoly keep doing R&D, Katsoulacos and Ulph (1998) predict whether an RJV would operate one or two labs depending on whether R&D *outputs* are (technical, not strategic) complements or substitutes. When R&D outputs are very close substitutes, cost considerations dominate such that an RJV would keep only one lab open. When R&D outputs are very strong complements, an RJV may prefer to keep two labs open.

Anbarci et al. (2002) adjust the KMZ-model and takes into account whether R&D *inputs* are complements or substitutes. Only non-competitive modes (i.e. R&D and RJV competition[26]) are looked at. They find that when complementarity between R&D inputs is high RJV competition dominates R&D competition in terms of technological improvement, industry profit and social welfare, irrespective of the level of exogenous spillovers. With low complementarity the conclusions of KMZ apply and R&D competition is preferred over RJV competition. For moderate degrees of complementarity, RJV competition is likely to be preferred on social welfare grounds for all levels of spillovers, but on grounds of technological improvement only when spillovers are low.

1.5.6 Knowledge stock and absorptive capacity

Most previously discussed papers have ignored the possibility that cost-reducing R&D expenditures and spillovers build on a pre-existing stock of technological knowledge. First, one could distinguish between pre-competitive research and competitive R&D (Vonortas, 1994). Pre-competitive or generic research generates a general, imperfectly appropriable, knowledge stock and

[25]Note that complementarity of R&D should not be confused with complementarity of final products. Katsoulacos and Ulph (1998) e.g. also distinguish between same and complementary industries. Röller et al. (1998) is another example where complementary industries are also modelled.

[26]Under RJV competition the spillover is set to one and profit is individually maximised.

competitive R&D draws from this knowledge stock and finally results in more appropriable and firm-specific cost reductions or product improvements. In the model of Vonortas (1994) both result in unit cost reductions. Focus is on cooperation in the pre-competitive stage. Conclusions are very similar to the ones of models where the spillover is set to one under R&D cooperation.

Second, in the tradition of Cohen and Levinthal (1989), the knowledge stock is often interpreted as a necessary condition for firms to be able to assimilate external knowledge. In other words, firms need *absorptive capacity* by doing R&D itself in order to reap benefits from incoming knowledge spillovers. Kamien and Zang (2000) redefine spilt over R&D by a Cobb-Douglas function that incorporates absorptive capacity effects. If a firm chooses to follow a narrow, firm-specific R&D program that does not generate spillovers to other firms, it also has no absorptive capacity. On the other hand, a basic approach yields a maximum level of outgoing spillovers and absorptive capacity. They find that absorptive capacity effects increase R&D investment.

Somewhat different conclusions are made by Grünfeld (2003) who introduces absorptive capacity effects in the AJ model by letting the incoming spillovers of a firm depend on its own R&D expenditures. He finds that R&D incentives of non-cooperating firms are only increased by absorptive capacity effects when the market is small. Furthermore, the critical spillover level at which cooperative R&D investment increases above non-cooperative R&D investment is higher than in the original AJ model.

1.5.7 Subsidies

Another topic that has been studied in the context of multiple stage models of R&D is the provision of government subsidies of R&D. Hinloopen (1997, 2000a,b, 2001) are examples of models that incorporate an analysis of R&D subsidies in the familiar two-stage models of R&D by adding a stage in which government decides on the height of an R&D subsidy. To cover the costs of the subsidies firms are taxed in the product market. The main finding is that optimally subsidizing non-cooperative R&D leads to a higher level of R&D and welfare than other modes, including R&D cooperatives with full information sharing, provided that spillovers are high enough. The highest welfare is reached when firms make their R&D decisions individually and fully share information (spillover of one). Finally, optimally subsidizing non-cooperative R&D without spillovers and cooperative R&D without spillovers yields the same outcomes for R&D and social welfare.

The study of Leahy and Neary (1997) provides a general[27] oligopoly model of R&D on the basis of which conclusions about optimal technology policy are made. Outcomes of different scenarios where firms either set their R&D in a first and their price/output in a second stage ("strategic behaviour") or set their R&D and price/output simultaneously ("non-strategic behaviour") are compared and first- and second-best optimal subsidies are calculated[28]. The results confirm earlier results that stress the importance of the degree of spillovers when considering the desirability of R&D cooperation from a welfare point of view, assuming that firms behave strategically. Without strategic behaviour, R&D cooperation is always preferred and does not mandate government subsidies as to obtain maximal welfare. Moreover, for most scenarios non-strategic behaviour is preferred on welfare grounds and requires lower subsidies.

1.5.8 Endogenous R&D cooperatives

In the part of literature discussed so far, the methodology that is used to investigate the issue of R&D cooperation is to compare outcomes (R&D decisions, profit, quantities, prices, social welfare, etc.) of an industry consisting of firms that do not cooperate in R&D with outcomes of an industry where all firms cooperate in R&D. Few attention is paid to whether R&D cooperatives are actually formed in equilibrium, how many are formed and how many firms they contain[29].

In the first place, the issue of RJV formation has been addressed assuming that only one RJV could be formed by two or more firms in the industry. In the models of Katz (1986) and Combs (1993) e.g., firms decide whether to participate in an RJV. In Katz (1986) firms also decide what R&D cost and information sharing rules to follow in the RJV whereby within-RJV spillovers are assumed to be larger than spillovers between members and non-members. The author proves that an equilibrium membership size exists that may be equal to all firms in the industry[30]. Forming an RJV is socially beneficial

[27]'Generality' in this context refers to non-linearity of demand functions and allowance for Cournot (quantity) or Bertrand (price) competition in the product market.

[28]The instrument of government policy to stimulate R&D is in this context subsidising. First-best subsidies cover both R&D and output subsidies, as two targets are to be controlled in the first-best solution (i.e. R&D investment and output), while second-best subsidies only cover R&D subsidies.

[29]Stability of RJVs has been addressed by Veugelers and Kesteloot (1994) and Kesteloot and Veugelers (1995) in a repeated-game framework, where it is assumed that firms can cheat on the part of knowledge sharing.

[30]E.g. if spillovers between non-members would be zero and R&D investment of members would be higher than investment of non-members, the equilibrium RJV contains all firms

when rivalry in the product market is low, when research is rather complementary, when important spillovers exist and when the formation of the RJV yields a high degree of information sharing. Combs (1993) develops a stochastic model where the probability of becoming an innovator can be increased with the amount of R&D expenditures and by joining an RJV. Within an RJV R&D is chosen cooperatively and the innovation can be accessed freely by all members. Findings are that as the probability of innovating increases, more firms enter the RJV, but the number of RJV members never exceeds the socially optimal number. Product market competition increases with the rate of research success, resulting in higher consumer surplus and total welfare.

Atallah (2003) assumes that higher within-RJV information sharing also yields more leakage to non-members. He finds that R&D spending of RJV members is reduced when the degree of outside leakage increases. Furthermore, with high outside leakage, the size of the RJV is also reduced ánd RJV members share less information while with low outside leakage, the RJV gets larger and full information sharing is maintained. Poyago-Theotoky (1995) finds that, for small rates of spillovers and R&D being a strategic substitute for non-cooperating firms outside the RJV, the equilibrium number of firms that form an RJV is lower than the socially optimal number which is all firms in the industry.

Kamien and Zang (1993) allow for an industry which is divided into several equally sized RJV cartels that set cooperative R&D levels and fully share information. They find that an industry with two RJV cartels yields lower prices than an industry-wide RJV if the produced goods are substitutes or if spillovers between competing firms are small.

In other models the number of RJVs that arises is endogenous. A first strand of literature, sometimes called the *coalition formation* literature, allows for *exclusive* groups of any size between a subset of firms in an industry where *exclusive* refers to the assumption that a firm can only participate in one coalition. An example of a model where cost reductions are *exogenous*, meaning that they are an immediate result of the coalition that is formed, is Bloch (1995). In a first stage firms decide in a non-cooperative and sequential game whether to form or enter in a coalition[31]. If all firms agree, then a coalition is formed. It is assumed that marginal production costs decrease linearly with the size of the coalition. In a second stage the firms are assumed to be Bertrand or Cournot competitors in a market of differentiated prod-

in the industry.

[31]One firm first proposes to a chosen set of firms to form a coalition and only if all the other firms agree, the coalition will be formed. The first firm that does not want to enter the proposed coalition, becomes the next initiator.

ucts. The equilibrium prediction (based on the Markov-perfect equilibrium concept) in the context of a linear model is that firms form two asymmetric associations, one containing 3/4 firms and the other containing the rest of the firms while the socially optimal outcome is one coalition that consists of all firms in the market. Further, it is found that firms form larger coalitions as products are more differentiated.

An implication of the assumption of exogenous cost reductions is that firms that are outside coalitions are unable to reduce costs by doing R&D. In Yi and Shin (2000) cost reductions are *endogenous* in the sense that all firms make R&D decisions, either outside or within a coalition. Findings are that on welfare grounds, an "exclusive membership rule" is preferred over an "open membership rule" for high spillovers[32]. On the other hand, the equilibrium RJV structure is mostly not the socially efficient outcome which is as in previous models an industry-wide RJV. Greenlee and Cassiman (1999) find similar results for high spillovers and relatively low R&D costs, given competition in the product market. For very high spillovers and low R&D costs, product market collusion may even be desirable on welfare grounds.

At the same time a related but different approach to model R&D collaboration has evolved, i.e. the literature on *networks*[33]. Here, coalitions between firms are pair-wise and non-exclusive (a firm can be in more than one coalition, therefore the term 'network' is more appropriate). Goyal and Moraga (2001) were the first to investigate the issue using a network approach with endogenous cost reductions. Firms have to decide in a first stage whether they will form collaborative links with other firms which is presented as a binary variable. If a coalition is formed, spillovers are complete within the coalition. In the second stage firms choose their R&D effort individually, as in a non-cooperative game, and in a third stage firms make their familiar production decisions. Within this framework the effects of the formation of symmetric as well as asymmetric networks on R&D behaviour are examined for firms that compete in a homogenous goods market and for firms that operate in independent markets[34]. Findings are that, irrespective of the market setting, the formation of a complete network is strategically stable. Only when markets are independent, this network is the unique strategically stable network. In homogenous goods markets, the level of collaboration in the complete network may be too high from a social welfare and industry-profit

[32]Under the exclusive membership rule, existing RJV members have to agree for an outsider to join the RJV, which is not the case under the open membership rule.

[33]See Goyal and Morago-González (2002) for a literature overview that incorporates models of vertically related firms.

[34]In an independent market individual R&D decisions do not influence the level of competitiveness.

maximising perspective, and a partial network is optimal. In the independent markets, it is socially optimal ánd industry-profit maximising to form a complete network.

In Goyal and Joshi (2003) a similar model is developed to investigate the link between firms' incentives to cooperate and the nature of market competition. Cost reduction in the model is *exogenous* which implies that only firms that enter a coalition, can reduce marginal production costs. Additionally, costs of forming links can be low or high. With small linking costs, the complete network is uniquely strategically stable and welfare-maximising under quantity competition. With high linking costs, asymmetric networks are stable, but it is unclear which networks are welfare-maximising. Under price competition, the unique stable network is an empty one, independent of the level of linking cost, while an asymmetric network is welfare-maximising.

1.6 R&D cooperation and price collusion

In the models that are overviewed so far, a crucial assumption on which most findings are based, is the assumption of independence between the decision to cooperate in R&D or to enter an RJV and the decision to cooperate in the product market. Indeed, by using the backward induction rule the equilibrium prediction that always results is competition in prices or in quantities. The question naturally arises whether this assumption is a valid one, whether cooperation in the R&D stage does not spill over to collusion in the product market[35]. This question has been looked at in some of the above papers (see e.g. Hinloopen, 1997) but formal modeling has been left for others[36].

A first way of dealing with the topic is to assume that cooperation in R&D automatically extends to cooperation in the product market. An example of this approach is Poyago-Theotoky (1997)[37] who sets up a model with product innovation and without cost sharing between firms. The underlying assumption that cooperation in R&D also extends to the product market

[35] A nice overview of the existence of multi-R&D-project and multimarket contact between firms in RJVs that are formed under the National Cooperative Research Act in the US is provided by Vonortas (2000). The author suggests that the scope for collusive play in the product market is enlarged by the combination of multiproject and multimarket contact.

[36] In Kline (2000) conditions are derived for a cost paradox to occur at the non-cooperative equilibrium, which refers to industry-wide cost-reductions that enhance competition such that profit finally falls. Under these conditions and when spillovers are less than perfect, cooperative firms reduce their research and may use the RJV to reduce product market competition.

[37] See also the previous section 1.4.2.

by the setting up of a common price for the "superproduct" that results from the RJV formation is necessary for firms to have incentives to form an RJV. As already mentioned, the main conclusion is that cooperation in R&D (that extends to the product market) is welfare enhancing when the quality improvement of the resulting new product is high or when R&D is relatively inefficient and has high decreasing returns.

A repeated-game framework is another approach to examine the relation between the two forms of cooperation. In Martin (1995) e.g., the effects of R&D joint ventures on the pervasiveness of tacit collusion in the product market are examined in a patent race model without spillovers. The author uses a non-cooperative repeated-game framework and assumes that firms follow a trigger strategy with product market collusion being an equilibrium strategy when the present value of profits gained from colluding is larger than the present value of profits gained from defecting. It is found that forming an R&D joint venture makes it more likely for tacit collusion to be sustained in the product market.

Another example of the second approach is van Wegberg (1995). His analysis is based on an extension of d'Aspremont and Jacquemin (1988) to a model with three firms and products that are imperfect substitutes. In the paper some specific cases are identified in which the formation of an R&D alliance of two out of three firms could lead to collusion in output in an infinitely repeated non-cooperative game context.

Further, in Cabral (2000) interactions between R&D and price decisions are examined in an infinite duopoly framework where firms are to make R&D and price decisions simultaneously. Only if R&D is successful, higher profits are gained. The findings are that self-enforcing R&D agreements that increase R&D towards an efficient level decrease prices while R&D contracting results in increased prices.

Finally, Lambertini et al. (2002) examine the interplay between product R&D and pricing decisions in a non-cooperative framework and find that joint product development decreases horizontal product differentiation and thereby destabilises collusion. When firms keep developing their products independently, there is more horizontal product differentiation which can facilitate price collusion.

1.7 Conclusion

R&D behaviour of firms in oligopoly has attracted a great deal of attention of IO theorists. The issue of R&D cooperation has mainly been examined in the context of non-tournament models where R&D is often assumed to be cost-reducing. A general result, whether the underlying model is symmetric or asymmetric, of a tournament or non-tournament kind, related to process or product R&D, etc., is the finding that the level of knowledge spillovers is important in determining whether firms' R&D incentives, profit and social welfare are higher/lower if firms cooperate in R&D compared to when they do not cooperate. Moreover, if either pre-cooperative or at least post-cooperative spillovers are above a certain threshold, R&D cooperation would be preferred on welfare grounds in a symmetric industry while otherwise R&D competition is preferable.

Factors have been identified that may increase or decrease the desirability of the formation of RJVs on welfare grounds. First, a low degree of rivalry in the product market seems to make the formation of RJVs more desirable. Allowing for *ex post* asymmetry of cooperative R&D decisions may also improve total welfare effects of R&D cooperation since a non-cooperative regime no longer prevails for low spillovers. Further, if firms do not behave strategically in the R&D stage and thus decide simultaneously on R&D and product market actions, R&D cooperation is always desirable, irrespective of the size of spillovers. R&D cooperation is also always desirable if it implies full information sharing.

RJVs are not always desirable though. If they are mainly created to reduce competition in the product market (cfr. negative strategic effects of cooperative R&D and the cost paradox), they may not be welfare-improving, even for industries with high spillovers. The probability of price collusion may increase when cooperative R&D agreements are formed, which should be taken into account when evaluating the formation of RJVs. On the other hand, collusion in the product market does not always reduce welfare compared to fully non-cooperative decisions. It does not e.g. when spillovers are high and products are to a certain extent differentiated or when product quality has increased a lot as a consequence of the RJV formation.

Whether firms have incentives to engage in industry-wide R&D cooperation also depends on a number of factors. In an *ex ante* symmetric duopoly industry firms prefer to cooperate in R&D—provided that the cooperative R&D level can be credibly committed to—since profits they then gain are higher than under R&D competition, irrespective of the size of spillovers. In a non-cooperative context, where the cooperative R&D level cannot be enforced, firms also have some incentives to cooperate in R&D, but the SPN prediction is R&D competition.

If initial unit production costs or spillovers are *ex ante* asymmetric or if R&D decisions are *ex post* asymmetric because of the symmetric equilibrium being unstable, profits are sometimes higher if firms do not coordinate their research activities. As such, firms would naturally prefer not to cooperate in

R&D while R&D cooperation may still yield a higher consumer surplus. In the case of cost asymmetries, if products are enough differentiated and asymmetries are not too large, incentives to form an RJV may be high enough.

In an oligopoly, industry-wide R&D cooperation is usually the most socially beneficial mode, but it is not necessarily the equilibrium prediction. Conclusions depend on whether a firm can participate in only one cooperative R&D project or in several. But again, the degree of product differentiation positively affects incentives to form and welfare effects of a wide R&D agreement.

To conclude, before deciding whether to promote R&D cooperation in a certain sector, a government should have an idea on the characteristics of the sector. The extent of exogenous knowledge spillovers, the number of firms in the sector, the size differences between firms, the willingness of firms to share information, the (difference in) R&D costs, the degree of product differentiation etc., are important factors that should influence this decision. Furthermore, policy makers should also realize that cooperation in the R&D stage may translate into cooperation in the product market. Empirical and experimental research can provide more information on these issues.

Chapter 2

Empirics of R&D cooperation and spillovers

2.1 Introduction

It became clear in chapter 1 that knowledge spillovers play an important role in game-theoretic models of R&D cooperation. First, under the assumption that firms cannot control the information flows between themselves and other firms, spillovers are important when comparing R&D cooperation modes with R&D competition modes with respect to the level of R&D investment, total industry profit and social welfare. Second, with spillovers being under control of firms, they are naturally also important because in that case they represent a decision variable in the model. Given the importance of spillovers in the theoretical framework and the empirical evidence for the existence of important knowledge flows between firms (see e.g. Griliches, 1992), it would be a logical next step to find empirical regularities on the relation with R&D cooperation.

In the empirical literature on R&D investment, R&D cooperation and spillovers we find two distinct approaches related to two distinct research questions. The first approach closely follows (specific models discussed in) the theoretical literature surveyed in the previous chapter as to predict whether or not spillovers among firms in an industry are low or high. Spillovers are expected to be low (high), if R&D cooperation has decreased (increased) R&D investment. An overview of papers where this approach is followed is given in section 2.3.

The second approach rather expands the theoretical literature by examining the effect of spillovers on incentives to cooperate in R&D. There exists a strand of empirical literature on the determinants of R&D cooperation and on profitability of R&D cooperation but focus has been mainly placed on the effects of firm size, R&D effort or intensity and market structure variables in general[1]. The relation between R&D spillovers and incentives to enter into cooperative R&D agreements has only very recently been studied empirically. We provide an overview of this approach in section 2.4.

Before having a closer look at these empirical analyses, we present in section 2.2 a short overview of the existing methodologies and results of measuring technological spillovers.

2.2 Measuring spillovers

'Technological spillovers' stand for all information and knowledge flows between economic agents. After having excluded the externalities that result from R&D inputs being purchased at a price less than their "full quality" price, which are sometimes called "rent spillovers" (Griliches, 1992) or "pecuniary spillovers" (Vonortas, 1997), these flows can arise through many different channels such as e.g. the movement of R&D personnel, the existence of formal and informal networks and meetings[2], publications related to research output, patent applications and reverse engineering. Consequently, technological spillovers are unmeasurable and finding the most appropriate proxy is a complicated matter[3].

Nadiri (1993) distinguishes two basic methodologies that have been used in the literature to proxy spillovers. First, there is the "technology flow" approach where firms and/or industries are positioned in a matrix with technological or other linkages. It is assumed that the total incoming spillovers of a firm or industry are equal to a (weighted) sum of knowledge stocks of other firms or industries, where the knowledge stock is calculated on the basis of e.g. R&D investment, R&D personnel, number of patents or any other innovation variable. The calculation of the weights is often based on a measure of technological distance (developed by Jaffe, 1986) and sometimes on a measure of geographical distance given the assumption that the closer firms or industries are in their technologies or in their geographical location, the higher the probability of knowledge flows. Measures of technological distance are

[1]Clear overviews are in Veugelers (1998) and Belderbos et al. (2003). See also e.g. Vonortas (1997).

[2]In a recent study, Dahl and Pedersen (2003) report results of a survey that provide evidence for the existence of important knowledge flows through informal contacts between employees of firms within networks.

[3]Vonortas (1997) further distinguishes "network spillovers" that are present when the success of a new R&D project and as such the incentives to start a new R&D project strongly depend on other complementary R&D projects or technologies.

often based on patent data in the assumption that spillovers between firms or industries are higher when patent activities overlap, but other measures, such as e.g. the share of scientists in total personnel (Kaiser, 2002b) or the number of cooperative R&D ties (Dumont and Tsakanikas, 2001), have also emerged. Since the emergence of new surveys such as e.g. the *Community Innovation Survey* (CIS) which includes questions on appropriability of research results and on usefulness of outside sources of knowledge, the weights can also be calculated in a direct way (Kaiser, 2002b).

Another approach to measure spillovers is the "cost or production function" approach[4] (see e.g. Bernstein, 1989; Coe and Helpman, 1995; Capron and Cincera, 1998; Rouvinen, 2002). Basically a cost or production function is estimated where next to the usual right-hand side variables, i.e. output and relative factor prices of variable and fixed inputs including R&D in the case of a cost function approach or stocks of variable and fixed inputs including the R&D stock in the case of a production function approach, similar variables that represent *other firms'* R&D stock are added to the equation. The estimated coefficients of these other firms' R&D stock variables give an indication of the degree of spillovers between the firms.

In any case, irrespective of the approach used, the general conclusion that can be made on the basis of empirical studies is that knowledge spillovers between firms and industries exist and than they are potentially important.

2.3 Relation between R&D cooperation and R&D effort

When closely following the standard theoretical IO literature, R&D cooperation would stimulate R&D expenditures of the participating firms if spillovers among these firms are high. As such, the main aim of entering the cooperative R&D agreement can be assumed to be internalising spillovers by eliminating free-rider effects. On the other hand, when R&D cooperation would decrease R&D expenditures, the formation of the R&D cooperative can be assumed to be aimed at cost-sharing. In this case, spillovers among the participating firms will be low.

In Vonortas (1997, chapter 7) industry- and firm-level analyses are performed of the effect of RJV formation based on the US *National Cooperative RJVs Act (NCRA)* on R&D intensity. Only for some industries it has been found that RJV participation decreased R&D intensity, thereby providing

[4] For literature overviews we refer to Nadiri (1993) and Cincera and van Pottelsberghe de la Potterie (2001).

support for cost-sharing motives to be important when engaging in R&D cooperation. For other industries, and in general, effects are statistically insignificant.

Based on micro-aggregated data of the first *Community Innovation Survey (CIS)* on four manufacturing industries Lambertini et al. (2004) derive some empirical evidence on R&D behaviour of firms in general, and of Stackelberg leaders and followers (see their model in sections 1.5.1 and 1.5.2). By employing simple analyses of variance, the authors find that R&D investment, and in the textiles and clothing industries also R&D intensity, of cooperating firms is higher than of non-cooperating firms. This should indicate that pre- and or post-cooperative spillovers are high, especially in the textiles and clothing industries. Other ANOVA tests indicate that spillovers[5] are larger among firms that cooperate in R&D than among firms that do not cooperate, except in the textiles industry.

Furthermore, if in each industry Stackelberg leaders are characterised (based on the Linda index), the authors find that these leaders invest more in R&D than the followers. Leaders in the textiles and clothing industries also have higher R&D intensities. Following their model, this indicates that control over spillovers is relatively low and that spillovers from the leaders to the followers are low.

Röller et al. (1998) also partly[6] apply this approach and find—on the basis of data coming from US *NCRA* firms—that within and between some industries cost-sharing is more important while for other industries, internalising the free-rider effect seems to be more important. In general, the cost-sharing effect dominates though. Results also indicate that RJVs among firms of similar size (*symmetric* firms) and large RJVs are better in internalising spillovers.

2.4 Spillovers as incentives to cooperate in R&D

An established result from the IO literature where spillovers are assumed to be exogenous is that in general, R&D cooperation is only welfare-enhancing if (either pre- and post-cooperative or at least post-cooperative) spillovers between firms are above a certain threshold level. But since in these models

[5]Measured as the product of R&D intensity and the sum of R&D investment of other firms in the same industry and the same country.

[6]They also estimate whether cost-sharing motives or motives of internalising spillovers are important for RJV formation. See section 2.4 for their results on this.

profits of firms are higher under R&D cooperation compared to R&D competition, irrespective of the spillover level, it would *ceteris paribus* always be advantageous for firms to cooperate in R&D. A natural question would then be whether firms' incentives to cooperate in R&D are actually influenced by spillovers.

As mentioned in section 2.3, Röller et al. (1998) examined which motives—motives of cost-sharing or motives of internalising spillovers (i.e. eliminating free-rider effects)—are most important for US *NCRA* firms, where cost-sharing and internalising spillovers are approximated by a measure of how firm-level R&D changed. They further examined to what extent asymmetries and product complementarities are important for the formation of RJVs[7].

The dependent variable was created by matching all firms in pairs and is equal to one if the pair participated in an RJV and equal to zero otherwise. Control variables that enter the equation are the size of the RJV, the number of RJVs the pair participated in, industry dummies that indicate whether both firms are in the same industry and dummies that indicate the different industries of the firms.

On the basis of the results of their probit estimation procedure the authors conclude that RJVs among firms of similar size (*symmetric* firms) and large RJVs tend to be formed more often. In general, the cost-sharing effect is more important in explaining the probability of RJV formation than the free-rider effect. Finally, for some industries the existence of product complementarities can stimulate the formation of RJVs.

Recently, econometric analyses have been carried out that identify the effects of spillovers on R&D cooperation. Examples are a study of Belgian firms on the basis of the European *CIS* (Cassiman and Veugelers, 2002), a study of German service firms (Kaiser, 2002a), a study of European firms that participated in *EU Framework Programmes* and *Eureka* projects (Hernán et al., 2003) and a study based on Dutch *CIS* data (Belderbos et al., 2003). In the papers cross-sectional probit or logit estimations have been carried out of an equation with the dependent variable being the probability that a firm enters a cooperative R&D agreement with at least one other firm. The econometric issue of possible simultaneity between the decision to cooperate in R&D and right-hand-side variables as R&D intensity has been dealt with in different ways.

Cassiman and Veugelers (2002) have distinguished between the effects of incoming and outgoing spillovers on the probability of entering a cooperative R&D agreement. Incoming spillovers are firm-specific and are measured on

[7]The empirical part in their paper is based on a model they developed in a first part. We refer to section 1.5.2 in the previous chapter for more details of the model.

the basis of *CIS* questionnaire ratings of the importance of publicly available information of different types for firms. On the basis of similar ratings of the effectiveness of methods for protecting products and processes, a proxy for outgoing spillovers (or appropriability) has been created. In the same questionnaire firms were asked whether they have participated in a cooperative project, which provides a basis for the (binary) dependent variable. Other variables added to the econometric equation are firm size, a permanent R&D dummy, industry level legal protection and cooperation, proxies for cost- and risk-sharing motives and a proxy for access to complementary knowledge.

The most important finding of the two-step probit estimations[8] is that the probability of firms cooperating in R&D is higher when incoming spillovers are high and outgoing spillovers are low. Further, cost-sharing is found to be an important motive for cooperation in R&D while risk-sharing is not. Note that these results are based on data of firms that are mainly vertically related or cooperate with research institutes or universities. Only about 10% of the firms in the data are horizontally related competitors. This naturally makes it difficult to evaluate theory—which is mainly based on models of horizontally related firms—by their empirical results.

Kaiser (2002a) takes simultaneity issues into account by estimating in a first step an equation of cooperation choice and in a second step an equation of innovation expenditures[9]. A distinction between vertical and horizontal spillovers was directly derived from survey data. Further variables related to the generality of R&D, research productivity, firm size and sector dummies are added to the cooperation choice equations.

Estimations indicate that horizontal spillovers seem to increase the probability to cooperate in R&D, while vertical spillovers are insignificant. Also research productivity, generality of R&D and firm size increase the propensity to cooperate. In the innovation equation, a positive impact of joint research, horizontal spillovers and research productivity has been found, and an inverse U-shaped impact of research generality.

Also in Belderbos et al. (2003) different types of R&D agreements and spillovers are considered. The decision to enter three types of R&D agreements, i.e. horizontal, vertical and institutional, is jointly determined. Spillovers are subdivided into firm-specific horizontal and vertical spillovers and industry-specific outgoing spillovers. Next to control variables as R&D intensity and firm size, variables from the management literature that influence

[8]Two-step estimations were done to correct for possible endogeneity of the spillover and permanent R&D variables.

[9]The author also models the decision of the type of partner to cooperate with, by making a distinction between vertical cooperation and horizontal and mixed cooperation. For results on this, we refer to the paper.

the probability to cooperate in R&D, such as cost, risk and organizational capability constraints and the rapidness of introduction of new products, are added to the equation. Dummies for being part of a group, for being a multinational firm, for being part of the service sector and for receiving an R&D subsidy are also included. As to mitigate problems of endogeneity, all time-dependent right-hand-side variables are lagged by two years. Furthermore, similar estimations are done for a group of firms that have been part of a cooperative R&D agreement in 1998, but not in 1996, as to check the robustness of the findings.

The findings regarding between-firm spillovers are that they are not significant in explaining horizontal cooperation, but vertical spillovers positively influence vertical cooperation. Incoming spillovers from universities and research institutions have a positive impact on all forms of cooperation.

In the study based on data of European firms done by Hernán et al. (2003) the probability for business units to participate in cooperative R&D projects is explained by variables that are similar to the ones in previous studies. An important characteristic of their analysis is that they use a large control group that is representative for the whole population of European firms[10]. Spillovers are measured on the industry level and are proxied by the average number of months before the diffusion of an innovation in the industry[11] and the effectiveness of patents in the industry, both based on previous analyses. Also R&D intensity at the industry level is included to control for possible differences in potential cost reductions across industries. Other variables that are included are the market concentration in the industry, firm size, the market share of the firm, the cumulated number of past participations to measure experience in R&D cooperation and country dummies. Problems of endogeneity, are, as in Belderbos et al. (2003), dealt with by lagging all time-dependent right-hand-side variables by two years.

A first important finding is that, contrary to what has been found by Cassiman and Veugelers (2002), outgoing spillovers have a positive effect[12] on the probability that firms cooperate in R&D. RJVs are also more likely in industries where technological knowledge diffuses rapidly, in more concentrated industries, among large firms and among firms that have past experience with participation in European cooperative projects. With respect to differences between countries, the authors find that mainly firms in smaller countries participate in projects funded by the EU, according to them because firms

[10]In Cassiman and Veugelers (2002) and Kaiser (2002a) the samples only consist of firms that are expected to be innovative in a certain period.

[11]The authors classify this as a spillover variable, but the variable rather measures the time lag before technological knowledge is actually diffused.

[12]Effectiveness of patent protection has a negative sign.

in large countries can easier find partners in their own country.

2.5 Conclusion

Empirical studies have recognised that knowledge spillovers between firms in the same industry and firms in different industries exist and are potentially important. Whether they influence the decision to enter into cooperative R&D agreements is less clear. In general, incoming spillovers are found to increase the probability of R&D cooperation while the effects of outgoing spillovers are ambiguous.

It is quite hard to find empirical regularities, which is not surprising given the differences in data sets that underlay econometric estimations, in estimation methods and in ways of defining or computing proxies that should represent variables found to be important in the theoretical literature on R&D cooperation, such as e.g. (knowledge) spillovers. Moreover, results are often industry-specific. Still, some results seem to be more general than others. First, R&D cooperation is more probable among larger firms and in more concentrated industries. Furthermore, evidence has been found for cost-sharing motives being important for firms when deciding to cooperate in R&D. And finally, especially general and basic R&D seem to be the subject of cooperative agreements.

We conclude that empirical attempts to test or improve IO models of R&D cooperation are still scarce which is probably due to a lack of firm-specific data, or better, of *adequate* firm-specific data. In the first place, R&D and related data are known to suffer from some specific problems, such as e.g. discontinuities in time series and ambiguous interpretations of R&D. Furthermore, it is also difficult to find or calculate empirical equivalents for theoretical variables as e.g. spillovers and it is not clear whether these capture the same features as in theoretical models. A complementary way of investigating the relation between R&D cooperation and technological spillovers would be to impose (some) features of theoretical models in the laboratory and test in experiments whether specific theoretical assumptions or predictions are valid in such a simple, but real, environment.

Chapter 3

Laboratory research on R&D and related games

3.1 Introduction

The aim of this chapter is to provide an overview of experiments that are related to the non-cooperative or cooperative R&D models as examined in chapter 1. In section 3.2 we overview the scarce literature on R&D experiments that are mostly based on non-cooperative R&D games. The experiments are either mere tests of theoretical predictions or they serve to gain further inside on the R&D decision process. We have not found examples of experiments on standard cooperative (process) R&D games as they exist in the IO literature.

Cooperation has been studied in different than R&D contexts, i.e. in the context of pricing and quantity games (oligopoly games) and in the context of public goods/bads games. Oligopoly games are related to the R&D models in two ways. First, strategic interactions in R&D and in product markets have similar characteristics, and second, the second stage of R&D models mostly is a pricing or quantity decision stage. The link between R&D decisions and decisions in public goods/bads games concerns externalities of actions. In section 3.3 some of the most important conclusions that are based on these related experiments are put together.

3.2 R&D experiments

In Isaac and Reynolds (1986, 1988) results of a static experiment on a stochastic invention model where the probability of producing a practically relevant innovation depends on the amount of R&D investment are reported. The

R&D decision was operationalised by letting subjects choose a number of draws with a constant cost. The underlying model is actually a single-period model of a tournament type where the emergence of several winners is not excluded by the model or by assumption. If the race had several winners, they simply shared the prize. As such, the underlying model is not one of (continuous) timing. An experimental environment without perfect appropriability was compared with a winner-take-all environment. Partial appropriability was exogenously determined by the experimenters and was introduced by allowing each subject to receive a positive profit, as long as at least one of the subjects innovated (as e.g. in Stewart, 1983). Another treatment variable was market structure. Part of the experiments respectively contained four and nine sellers.

The authors found strong support for most of the conclusions of tournament models (as in 1.2.1). First, they found that without spillovers, subjects strongly overinvested in R&D compared to the cooperative or social optimum. A second result is that an increase in the number of firms reduced individual R&D investment but increased total industry investment. Finally, experimental evidence also indicated that with spillovers R&D investment was lower than without spillovers.

Hey and Reynolds (1991) and Zizzo (2002) are examples of experiments on dynamic multi-stage patent races. The former experiment is based on the deterministic patent race in Fudenberg et al. (1983), and the latter on the stochastic patent race in Harris and Vickers (1987), but in both models firms go through a pre-specified number of steps before ‘winning an innovation’. In Hey and Reynolds (1991) subjects simultaneously and independently had to choose whether to invest nothing in R&D (going zero steps) or to invest in R&D at a low (going one step) or high rate (going two steps), where going two steps costs more than going two times one step. Both subjects that reached the winning state at the same time shared the prize[1]. In Zizzo (2002) firms could choose to invest a number whereby the cost of investing was calculated according to a quadratic cost function. The winner of each round was randomly chosen with the probability of winning depending on the rate of R&D investment.

Both experiments failed to provide evidence for the underlying models that predict that if firms are tied, they invest in R&D at a high rate and that if they lag behind, they invest less or nothing at all. Zizzo (2002) did find evidence for the theoretical prediction that tied competitors invest more the closer they are towards the end of the race. Since the Nash equilibrium of their game might have been to complex to understand, Hey and Reynolds

[1]As such, the underlying model is not a ‘pure’ tournament.

(1991) performed a verbal protocol analysis in a later experiment as to have a better idea on the decision processes of the subjects. Their main conclusion still was that Nash equilibrium strategies were not always followed.

A somewhat different approach is used in Sbriglia and Hey (1994) who stress the complexity of an R&D decision problem rather than focusing on a comparison of experimental behaviour with theoretical (Nash) predictions. In their experiment subjects had to find an unknown combination of a number of different letters of the alphabet during an endogenous number of rounds, each fixed in time. At the end of each round they could buy information at a fixed cost on the amount of letters in their proposed trial combination that were correct. High- and low-cost treatments were included and in part of the treatments the information was noisy and to gain full information on the amount of correct letters, additional costs were necessary. At the end of each round subjects were also informed on the performance of their competitors.

Main results are that winners applied a successful search strategy and generally invested more than losers. Losers used similar search strategies, but invested not enough or were not lucky. Furthermore, competition resulting from joint discovery enhanced investment and decreased the number of rounds before completion of the task[2]. In the noisy information treatments, the number of incompetent and random players was higher than in the deterministic information treatments and experiments lasted more rounds.

Examples of dynamic experiments where subjects were to make R&D and price/quantity decisions are Isaac and Reynolds (1992) and Jullien and Ruffieux (2001). None of the two examples is based on a specific theoretical model. In Isaac and Reynolds (1992) a posted-offer market has been simulated by the computer. In the first five periods, subjects were only to make price and maximum-selling-quantity decisions and beginning with period 6, subjects could also make R&D decisions which resulted in lasting cost reductions according to a stochastic invention mechanism (as in Isaac and Reynolds, 1986, 1988).

The experimental results of four-sellers markets give support to behaviour that the authors classify as Schumpeterian competition characterised by a combination of engagement in costly innovation and falling prices and by rising concentration. Market prices under monopoly, on the contrary, tent to fall more slowly than under oligopoly. As such, the benefits flew more to consumers under oligopoly than under monopoly. Oligopoly R&D investment was generally lower than the social optimum, except in the last periods, but

[2]These results seem to correspond to some of the predictions of multi-stage patent race models as tested in Hey and Reynolds (1991) and Zizzo (2002), but are based on descriptive rather than statistical analyses.

it is unclear whether it was close to an equilibrium prediction.

In Jullien and Ruffieux (2001) the market is characterised by a double auction with human buyers. They introduced spillovers by letting R&D decisions of a firm yield industry-wide cost reductions with a time lag. Treatments with deterministic innovation with certainty over the outcome of the R&D investment and stochastic innovation, as in Isaac and Reynolds (1992), were run.

Market prices generally converged towards their competitive level and markets were thus efficient. When all oligopolists simultaneously gained a cost reduction that shifted the aggregate supply curve downwards (cfr. spillovers), adjustment of market prices to their new competitive level in the deterministic games was slower and benefits of the innovations initially solely accrued to producers. Furthermore, uncertainty caused more heterogeneity in R&D decisions and yielded a categorisation of leaders, challengers and followers. Leaders invested and kept investing, challengers tried to catch-up the closer they were to the leader of the race and followers mainly stopped investing, which is consistent with predictions of some multi-stage patent race models. Uncertainty also yielded prices that are further away from equilibrium predictions. Finally, only R&D decisions with uncertainty are reduced by spillovers.

Finally, we consider two recent but unpublished experiments on the formation and evolution of RJVs in a patent race framework (i.e. Silipo, 2001, 2003). The experiment in Silipo (2001) is based on a dynamic patent race model with two firms, developed in the same paper (see 1.4.1). In some treatments subjects were assumed to collude in the ensuing product market while in others they were assumed to compete, with collusion yielding higher profits. Coinciding with theory, in the high-profit (collusive) treatment more RJVs were formed than in the low-profit treatment. Also coinciding with theory, with a large gap in knowledge between subjects at the beginning of the race, RJVs were not formed. With a smaller gap, theory predicts that they are not formed but in the experiment they were formed, and only in the high-profit treatment less frequently compared to the treatment without a gap. Finally, experimental evidence also supports the theoretical prediction that R&D effort with cooperation is lower than without cooperation.

The experiment in Silipo (2003) is less related to a specific theoretical model. In markets with four and seven producers, it has been investigated how endogenous RJV formation and breaking down evolved in time. In a dynamic patent race, subjects had to propose in each period with whom to cooperate following an exclusive membership rule (as in 1.5.8) and how much to invest in R&D. It turned out that winning a race was more probable if being part of a wide R&D coalition. But only in four-player races there was industry-wide cooperation. Another result was that leaders with an initial advantage started to cooperate among themselves, which was mostly maintained in the four-player races. In seven-player races some evidence for catching-up behaviour of followers was found. Finally, contrary to previous results on two-player races, R&D investment seemed to be stimulated by the possibility to form competing RJVs.

3.3 Related experiments

3.3.1 Oligopoly experiments

Many IO experiments have concentrated on identifying conditions under which prices or quantities of oligopolists correspond to theoretical benchmarks. As in a non-cooperative R&D game, these theoretical benchmarks usually correspond to a non-cooperative or Nash equilibrium and a cooperative level of prices or quantities where the cooperative option yields more profit than the non-cooperative option. An overview of oligopoly experiments is given by Holt (1995).

A first general result is that in oligopolies with more than two firms, behaviour is usually not anti-competitive and Nash equilibrium predictions often perform well. In duopoly experiments, on the other hand, there is a larger probability that prices or quantities are above or below their predicted equilibrium level. Tacit collusion[3] has already been observed in duopoly experiments, especially in multi-period experiments that consist of the repetition of single-stage games (see also Davis and Holt, 1993; Keser, 2000). Full efficiency is not always obtained, though.

According to Holt (1995), tacit collusion is more probable in duopoly experiments because a defecting firm is identified and can be immediately punished. Furthermore, in experiments with only two sellers, it is easier to monitor the decisions of the other firm. Experimental evidence for this hypothesis has been found by Huck et al. (2004). In Cournot markets with two firms, some collusion came out, in markets with three firms output was often at the Nash level while four-firms markets were even more competitive.

Another factor which has extensively been examined is non-binding communication. Effects of communication on pricing behaviour in experiments are not unambiguous though. Holt (1995) concludes that the effect depends on the trading institution and the incentives to defect at the margin. With posted prices and differentiated products, the effect is the largest. In Holt

[3]Tacit collusion refers to a situation where firms collude in a market by setting high prices or restricting quantity without having explicitly agreed on in a binding way.

and Davis (1990) evidence is found that prices initially increase after price announcements but that prices in the end return to their initial lower levels. On the other hand, Harstad et al. (1998) find that the announcement of prices leads to higher prices than the Nash equilibrium, though not as high as the joint profit maximization level. Cason (1995) comes to a similar conclusion but distinguishes effects of discrete and continuous signaling. Continuous signaling, where it is optional to send a signal, stimulates cooperation more which could imply that the simple sending of a signal indicates a willingness to cooperate. As such, communication may be important to build trust among the sellers (see e.g. Muren and Pyddoke, 1999). Thus, with an appropriate form of non-binding communication, tacit collusion may arise in experimental markets.

Other factors that may enhance cooperative behaviour in duopolies are symmetry in payoffs or costs (Mason et al., 1992; Keser, 2000) and the availability of information on the other firm's profit (Mason and Phillips, 1997). In Cason (1994) and Cason and Mason (1999) information sharing is a decision variable in the experiments in that subjects have the possibility to share information on demand and/or cost conditions before setting prices or choosing output. They find that information is often shared, even in situations where the scope for colluding is low, and that it may facilitate tacit collusion.

3.3.2 Public good/bad experiments

The non-cooperative R&D stage of an oligopoly model, given firms' expectations on prices or quantities in the second stage, is in a way related to a public good/bad game. If spillovers in the non-cooperative R&D game are complete, R&D decisions have positive externalities in the sense that profit of other firms increases as a firm raises its R&D investment. This mechanism of positive externalities also works in a public goods game, through the system of voluntary contribution.

The voluntary-contributions mechanism implies that each subject of a group has to decide how much of his/her initial endowment to *contribute* to the group[4]. After having made their decisions, the subjects receive—on top of what remains from their initial endowment—a certain return as a percentage of total group contribution. Contributing nothing corresponds to the Nash equilibrium and contributing everything to the cooperative optimum. In these games actions of a player also increase profits of other players. The opposite emerges without spillovers, as is the case in public bad games. In

[4]For overviews of public good experiments see e.g. Davis and Holt (1993), Ledyard (1995) and Roth (1995).

public bad games subjects are asked to *take* an amount from a group endowment. Public good experiments typically yield higher levels of cooperation than their public bad equivalents (Andreoni, 1995; Offerman, 1996; Willinger and Ziegelmeyer, 1999; Park, 2000) which in this context is often referred to as a framing effect.

It is generally found that in one-period games without repetition subjects do not behave according to the Nash equilibrium but rather cooperate to some degree, without reaching the Pareto-superior level. In experiments with repetition, it is common that subjects' behaviour evolves from cooperation in some first periods to free-riding in later periods (see e.g. Isaac and Walker, 1988; Ledyard, 1995; Andreoni, 1995). So, repetition leads to reduced contributions to the public good.

Roughly three possible explanations for this observation exist in the literature (see e.g. Davis and Holt, 1993; Fischbacher et al., 2001). First, subjects may learn to play the SPN equilibrium during the experiment which makes initial cooperation a mistake. Second, cooperation may be a consequence of strategic play and diminish or disappear when the other in a pair cheats. Third, some of the subjects may be conditional cooperators and only cooperate if others cooperate.

Davis and Holt (1993) and Ledyard (1995) give an overview of other factors that have influenced individual contributions to the public good. Controllable factors that increase contributions are e.g. the marginal per capita return, common knowledge and symmetry with respect to payoffs. Factors as economics training and experience with similar experiments also seem to increase the probability of free-riding but are less easy to control.

Isaac and Walker (1988) and Isaac et al. (1994) have investigated effects of group size in public good experiments and find that an increase in group size, when coupled with a decrease in marginal return, leads to more free-riding[5].

Finally, communication before the game is played, e.g. in the form of a simple cheap talk treatment, significantly increases contribution rates and consequently total group return. Beside this, repetition with communication tends to increase contributions (Isaac et al., 1985; Isaac and Walkers, 1988; Davis and Holt, 1993; Ledyard, 1995).

[5]That is when groups of 4 and 10 subjects are compared. Other conclusions are made when comparing group sizes of 40 with 100, but are less relevant to us as oligopolies have smaller group sizes.

3.4 Conclusion

Although the laboratory method would be an appropriate means of testing or improving theoretical R&D models, complementary to the econometric and other empirical methods, experimental economists have not paid attention to it yet. On the basis of experiments that did serve as tests for non-cooperative R&D models or that were aimed at gaining more insight in the complex innovative decision process, we tried to find some general trends in results.

In simple static R&D experiments, Nash equilibrium predictions of R&D decisions seem to perform well while in more difficult dynamic experiments, such as patent races and two-stage experiments with R&D and product market decisions, theoretical predictions are less supported by experimental behaviour. As such, subjects seem not to be able to "calculate" Nash strategies in more complex, dynamic environments. Recent experiments on RJV formation in a dynamic patent race did provide partial support for theoretical predictions, though.

However, in dynamic two-stage experiments with R&D and product market decisions, the evolution of prices or quantities was the central issue and less attention has been paid to comparisons of experimental R&D decisions with theoretical predictions. These experiments find support for substantial innovation. In general, whether R&D is either stochastic or deterministic, prices are found to be close to the competitive level which makes the benefits of innovation accrue almost fully to consumers. When spillovers are taken into account, such that all producers gain a cost reduction, in deterministic R&D games it takes more time for prices to adjust to their competitive level.

Finally, we provided a short overview of the main conclusions and factors that enhance cooperation in other oligopoly and public goods/bads experiments given the similarities with non-cooperative R&D games. Factors as number of firms or subjects in the market or group, repetition, experience and communication possibilities were found to be important in enhancing or limiting cooperation.

Conclusion

In this paper we have given an overview of theoretical, empirical and experimental IO literature on the relation between R&D cooperation and spillovers. While the topic is extensively documented in the theoretical literature, empirical and especially experimental analyses are scarce.

The scarcity of empirical (econometric) analyses is probably due to a lack of firm-specific data, or better of *adequate* firm-specific data. In the first place, R&D and related data are known to suffer from some specific problems, such as e.g. discontinuities in time series and ambiguous definitions on what R&D actually is. Furthermore, it is also difficult to find or calculate empirical equivalents for theoretical variables as e.g. spillovers and it is not clear whether they capture the same features as in theoretical models. And finally, the interrelatedness of R&D and other variables as market structure, firm size, profit etc., gives rise to econometric problems of simultaneity.

In the context of mainstream models of R&D cooperation and product market competition overviewed in the first chapter, one could raise the question whether firms' actual R&D decisions correspond to the theoretical predictions. E.g. do firms actually cooperate in R&D when they have possibilities to commit to a binding agreement and is the Nash equilibrium a good predictor of what firms will do without binding contract possibilities? And more importantly, are conclusions regarding R&D behaviour the same for different levels of spillovers?

An important research question, which has recently been given attention by econometricians, is whether incentives to cooperate in R&D are different for different levels of technological spillovers. Laboratory methods may be an important way—complementary to existing econometric analyses—to provide more clarity on this issue. We have pointed out in the first chapter that for low levels of technological spillovers, R&D decisions are strategic substitutes, and strategic complements for high spillover levels. These strategic features can be nicely copied in the laboratory, which is not possible in econometric analyses. Moreover, strategic interactions not only occur in an R&D context. Other contexts where strategic interactions play an important role are the product market in IO models (Cournot versus Bertrand competition) and adjustment of nominal prices after an anticipated money shock[6].

Further, an important factor that is mainly ignored in mainstream IO models of R&D is the link between cooperation in R&D and cooperation in the product market. It is mostly assumed—based on the assumption of perfect functioning of anti-trust laws—that firms compete in the product market, irrespective of how they behave in the R&D stage. But would it not be possible that cooperation in R&D 'spills over' to cooperation in the product market? If that is the case, welfare-enhancing effects of R&D cooperation are not that obvious any more. Given previous results of oligopoly experiments, different conclusions regarding the effect of R&D cooperation on cooperation in the product market could arise between duopolies and markets with more than two firms.

Why experimental economists have been reluctant to investigate these issues is not clear, given that laboratory methods have become a widely accepted research methodology in industrial organisation. Especially as a test for (assumptions of) simple theories, where strategic interactions are important, laboratory methods are a useful and additional tool because (part of) the simplifying conditions can be enforced in the lab. To summarise, laboratory R&D experiments can be complementary to econometric research and can serve as an important basis for the formulation of guidelines on how to further improve theoretical models.

[6]Fehr and Tyran (2002) compares scenarios of strategic substitutes and strategic complements in the context of adjustment of nominal prices after an anticipated money shock. They find that with strategic complements prices adjust very slowly to the new equilibrium, while with strategic substitutes adjustment is very quick.

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