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1. General Introduction

An intensive debate in the economic literature concerns the impact of market structure and market power on the incentives of firms to engage in innovative activities. This longstanding but indecisive discussion has been triggered by the conflicting views of Joseph Schumpeter and Kenneth Arrow. On the one hand, in one of his well-known hypotheses, Schumpeter (1942) argues that market imperfections, such as concentrated markets and market power, provide better incentives for firms to invest in innovative activities compared to perfect competition. On the other hand, Arrow (1962) claims that a monopolistic environment provides less incentives to invest in research and development (R&D) compared to a competitive scenario. After all, the gains resulting from an innovation for the monopolist equal the difference between the value of the innovation and his current profits whereas the gains for the competitive firm equal the full value of the innovation.

Subsequent theoretical studies have further illustrated this ambiguity. Overviews of this rich literature stream are provided by Tirole (1988), Reinganum (1989), Van Cayseele (1998) and Gilbert (2006). Moreover, also empirical studies yield diverging answers on the question whether market power encourages or inhibits innovative activity. For example, Malerba and Orsenigo (1999) provide evidence on the intense R&D activity by market leaders. Based on EU patent data, they show that, in general, a significant part of total innovative activity can be attributed to some large and persistent innovators, thereby supporting Schumpeter. However, Czarnitzki and Kraft (2004) find that challengers invest more in R&D than incumbents, which is then again in line of Arrow.

This thesis further contributes to the Schumpetarian discussion by analyzing the impact of market power and market structure on innovative incentives in three related studies. One specific topic of interest is the role played by spillovers in this analysis. In what follows, a more detailed introduction to these three studies is provided.

Study 1: Strategic investments of leaders and followers

The focus of the first study is on the incentives of leading and following firms to invest in R&D. A strategic investment model is set up in which leaders (innovators) invest in cost-reducing R&D before the followers (imitators). Moreover, it is assumed that the leaders also choose their output levels before the followers (Stackelberg competition). In other words, the role of a leader concerns both the technology as well as the market side. This assumption can be justified by the observation that, in some industries, the market leader is also often the first to innovate. For example, in the dredging industry, the big market players are usually also the innovators. Dependent on the exact sequence of the stages, two different settings are analyzed, i.e. an early and a late entrance setting.

To continue, the model also takes into account the presence of technological spillovers, which are known to be an important characteristic of the R&D process. Indeed, as was stated by Arrow (1962), the output of the R&D process is knowledge – about a new product, service or production process – and knowledge is a public good, as it is both non-exclusive and non-rivalrous in its use[1]. Consequently, R&D knowledge may spill over from one firm to another. Channels through which these spillovers may take place are for example company visits, personnel mobility and reverse engineering.

In this study, there may be spillovers among leaders, among followers and between these two groups of players. We furthermore allow the spillovers to be asymmetric, which is due to the assumed heterogeneity between firms, i.e. leading versus following. For example, it is no illusion to believe that leading firms may have different learning capabilities or absorptive capacities compared to followers supporting our reasoning that spillovers among leaders can be different compared to the spillovers among the followers.

It is furthermore assumed that leaders and followers are allowed to cooperate in R&D. After all, it is well-known that, due to the spillovers, firms are less willing to invest in

[1] A large body of literature has provided empirical evidence on the existence of technological spillovers. Overviews of this literature can be found in Griliches (1995), Geroski (1995), Kaiser (2002) and Sena (2004).

R&D as rivals can free ride on their innovative efforts. Consequently, firms may not invest sufficiently in R&D from a social welfare point of view[2]. This problem of underinvestment in R&D by private firms has urged policy makers to come up with instruments to enhance firm's incentives to invest in R&D. A well-known instrument, next to patents and R&D subsidies, is the allowance for R&D cooperation[3].

The prevalence of R&D cooperatives[4] has been the breeding ground for a large number of studies on the effectiveness of R&D cooperation. In this regard, the Industrial Organization (IO) literature provides rich game theoretical models analyzing the impact of R&D cooperation. Pioneering studies in this field are attributable to d'Aspremont and Jacquemin (1988) and Kamien et al. (1992), who consider a two stage model in which firms, producing homogeneous goods, invest simultaneously in cost-reducing R&D in the presence of symmetric technological spillovers before competing (à la Cournot) on the output market. Several extensions of these seminal papers have emerged and have been reviewed (De Bondt, 1997; Veugelers, 1998; Sena, 2004; Motta, 2004). However, most of these extensions analyzing R&D cooperation do not consider firm heterogeneity (leading versus following firms) and spillover asymmetry. Consequently, by introducing R&D cooperation among leaders or followers, further insights into the effectiveness of R&D cooperation as an R&D encouraging policy instrument can be obtained.

All in all, a four stage strategic investment setting with leaders and followers is analyzed. Spillovers can be symmetric or asymmetric and R&D cooperation among

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[2] Apart from spillovers, financial constraints and uncertainty may also contribute to the wedge between private and social incentives. It may indeed be difficult for firms to gather the necessary financial resources because of the high cost of external capital (Himmelberg and Peterson, 1994; Hall, 2002). Moreover, the R&D process is characterized by a high level of uncertainty. Especially at the beginning of a new research project, there is high uncertainty about its technological feasibility. In addition, even if the new product has been developed successfully, there is also uncertainty about the size of the market for a new product or service, which is called market uncertainty. It happens frequently that the size of the market for an innovation is under- or overestimated. And finally, there is also competitive uncertainty. One firm could complete the development of a new product ahead of a rival firm, which could result in pre-emption of the slower firm by the faster firm (Gilbert and Newberry, 1982). The distinction between these three different types of uncertainty stems from Hinloopen (1997a).

[3] For more on the effectiveness of patents, see for example the recent and comprehensive work of Bessen and Meurer (2008). Aerts and Schmidt (2008) and Hinloopen (1997a, 1997b and 2000) analyze the effectiveness of R&D subsidies on firms' incentives to invest in R&D.

[4] Since the 1960s, there has been a growth in R&D partnerships and this growth has accelerated since the (late) 1980s (Hagedoorn, 2002). Especially, a lot of R&D partnerships can be observed in the ICT and biotechnology sector.

leaders or followers is allowed for. The main research questions are then the following. Firstly, the impact of changes in the symmetric or asymmetric spillovers on leaders' and followers' R&D investments is analyzed and compared with the impact of (symmetric) spillovers in the two stage game settings in which an increase in the spillover diminishes efforts of R&D competing firms but encourages R&D expenditures of R&D cooperating firms.

Secondly, it is analyzed whether followers sometimes invest more than leaders, and if so, under which conditions this so-called technological leapfrogging is most likely to take place. The main point of attention here is the role played by spillovers. Furthermore, as leaders and followers can cooperate in R&D, it can be assessed whether R&D cooperation among leaders or followers may enhance or discourage leapfrogging opportunities. By doing so, additional insights into the impact of market power and structure on innovate incentives are gathered.

Finally, the impact of R&D cooperation on economic performance, in terms of R&D investments, profitability and welfare is analyzed and compared with settings with simultaneous moves. After all, in these two stage game settings, R&D cooperation, defined as the coordination of R&D strategies, yields higher R&D investments if and only if the symmetric spillover exceeds a certain threshold value, called the critical spillover. The same applies to consumer surplus and total welfare. Producer surplus is always higher with R&D cooperation (d'Aspremont and Jacquemin, 1988; Kamien et al., 1992). It is thus analyzed whether these tendencies also take place in the four stage game setting.

Study 2: Leadership persistence and technological leapfrogging in patent races without winner-takes-all.

Note that the model in the first study is static, as firms invest only once in R&D. However, in reality, competition for the market is more dynamic as firms tend to invest in R&D over time and continue investing until the innovation (a new product or a new technology) is found. At that moment in time, a prize is awarded to the innovator and all firms stop investing in R&D. This dynamic competition for the market is the topic of the second study of this thesis. More specifically, dynamic competition for the market is modelled by patent races, in which firms invest in R&D continuously over time and in which the probability of successful innovation depends on firms' R&D investments.

Patent races with one incumbent monopolist and one or more entrants are considered. The incumbent can be seen as the patent holder of a current technology, having a head start over its potential competitors in the race for the next innovation. For example, in the 1970s, EMI had a patent on the CAT brain scanner, but other firms, like GE and Technicare also searched for the next technology in the CAT scanner market, being the full body scanner.

So far, these patent races have only been analyzed under the assumption that the winner of the race is rewarded with the full value of the innovation, which is called winner-takes-all. In other words, when the prize for the winner is a patent on the innovation, current studies on patent races (with an incumbent and one or more entrants) have assumed that patents work perfectly. In that case, a patent provides the innovator with the exclusive right to its innovation for a certain period of time, by which a temporary monopoly position is granted on the new product, the new service or the new production technology.

However, despite the popularity[5] of patents, they may not always work perfectly, as has for example been illustrated by Mansfield et al. (1981). Based on a sample of 48 product innovations in the chemical, drug, electronics and machinery industries, they show that 60% of all patented innovations are legally imitated within 4 years. Moreover, imitations costs are in general (far) less than the R&D costs for the original innovator. For example, in the pharmaceutical industry, about 70% of total R&D costs of the innovator are incurred during the clinical tests. Generic drug manufacturers, however, are not required to repeat these tests, by which their (imitation) costs are lower than the innovator's R&D costs (DiMasi et al., 2003). Exemplifying the flaws in the patent system is the observation that large European industrial firms apply for patents on only 36% of their product innovations and 25% of their process

[5] Since the first modern patent was granted in 1474 in Venice, its use has been growing steadily over the years. Illustrative of this trend is the current number of patent applications: in 2006, there were approximately 208 000 patent applications at the European Patent Office, 400 000 at the United States Patent and Trademark Office and more than 400 000 at the Japan Patent Office.

innovations (Arundel and Kabla, 1998). Moreover, the patent holder does not always observe infringements and, moreover, if the patent holder would observe the infringement and the infringer, the company may lack legal expertise or financial resources to fight the infringement (Crampes and Langinier, 2002).

The result of all this is that, in patent races, losers can also reap some rewards of the innovation. It thus turns out to be interesting to analyze patent races in which rewards are shared between the winner and the losers of the race. Several reward sharing scenarios are looked at. Moreover, both exogenous and endogenous entry are analyzed. After all, it has been shown that, with winner-takes-all, assumptions regarding entry have dramatic consequences for the comparison of incumbent's and entrants' efforts when there is no sharing of rewards. Indeed, the entrants invest more than the incumbent when there is exogenous entry (Reinganum, 1985), but this result is reversed with endogenous entry (Etro, 2004). In other words, when there is winner-takes-all, technological leapfrogging is more likely in races with exogenous entry while monopoly persistence tends to be the rule in races with endogenous entry.

In this second study, it is then questioned whether and when sharing of rewards can alter the predictions of Reinganum (1985) and Etro (2004). Consequently, more insights are obtained into the role played by reward sharing (and thus the degree of patent effectiveness) in the process of leadership persistence or technological leapfrogging, both with exogenous and endogenous entry. Furthermore, also tendencies of expected profits are shortly dealt with. Finally, incumbent's and entrants' R&D investments are compared with the socially optimal investments.

Study 3: Cournot versus Bertrand competition with cost-reducing R&D and input spillovers

In the third study, the focus is on the impact of the mode of market competition on the incentives to invest in R&D and the concomitant implications for consumer surplus and welfare. More specifically, quantity (Cournot) competition is compared with price (Bertrand) competition when the market competition stage is preceded by a stage of investments in cost-reducing R&D by which production costs are lowered and, hence, market structure is endogenous. If market structure is exogenous, it is well known that consumer surplus and static welfare are higher with price competition than with quantity competition (Singh and Vives, 1984).

However, this standard finding may be altered when firms invest in R&D before they compete on the market. More specifically, static welfare can be higher with Cournot competition than with Bertrand competition when firms invest in product R&D to enhance product quality (Symeonidis, 2003). With cost-reducing process R&D, Qiu (1997) shows that static welfare can sometimes be higher when firms compete à la Cournot but consumer surplus is always higher with Bertrand competition.

In this third study, a further analysis of the economic performance of Cournot versus Bertrand markets is presented. A familiar two-stage model is considered. In the first stage of the game, two firms, producing substitutable products, invest in cost-reducing R&D in the presence of technological spillovers, followed by market competition (Cournot or Bertrand) in the second stage. Although this model is very similar to the model of Qiu (1997), two important differences need to be stressed. Firstly, in the analysis presented here, spillovers are considered to occur during the R&D process while Qiu (1997) assumes that R&D output spills over (thus when the R&D process is finished). In other words, input rather than output spillovers are considered. Secondly, the study presented here is the first to analyze the impact of R&D cooperation on the comparison of Cournot versus Bertrand competition when there is a precompetitive stage of R&D.

It is then analyzed which type of market competition mode yields the highest incentives to invest in R&D by which more light is shed on the impact of competition intensity on firms' R&D investment incentives. Furthermore, consumer and static welfare are compared under Cournot and Bertrand competition. Especially, the aim of the study is to see whether it is possible that less intense types of market competition (here Cournot) can sometimes result in higher welfare for consumers and society compared to more intense types of market competition (Bertrand).

The remainder of the thesis is organized as follows. Chapter two, three and four deal with these three studies in the same order as presented here. In chapter five, the main conclusions of the research are summarized in brief and some possibilities for further research are provided.

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2. Strategic investments of leaders and followers

Joint Work with Professor Raymond De Bondt

The focus of the first study is on a four stage strategic investment game in which leaders and followers invest competitively or cooperatively in cost-reducing R&D in the presence of symmetric or asymmetric spillovers. In brief, the main findings are the following. When the followers can free ride to a large extent on the R&D investments of the leaders, it is likely that the former invest more than the latter. Such leapfrogging opportunities can be discouraged by R&D cooperation among the leaders or stimulated by R&D cooperation among the followers. Furthermore, R&D cooperation has analogous effects on the level of R&D investments of leaders (followers) as in the more familiar two stage models with simultaneous moves. Thus, if the spillover is large enough, R&D cooperation among leaders (followers) results in higher investments than R&D competition. Finally, the study points out that, in industries with a small number of leading firms, society is better off when followers cooperate in R&D.

2.1. Introduction

Firms tend to be frequently involved in strategic investments in their attempt to achieve or maintain sustainable competitive advantages. Strategic investments may take many forms, such as expenditures to increase business and technological knowledge accumulation, advertising or service outlays to develop or maintain goodwill in the market, and investments directed at modifying product characteristics, production processes or features of the internal organization and/or the external institutional environment.

A number of the main characteristics of these investments is fairly well understood and is helpful in inspiring competitive analysis. Strategic investments, for example, tend to change the parameters of the market rivalry outcomes, they may hurt or benefit rivals and firms may have an incentive to temper or exaggerate efforts for strategic reasons. Some investments may involve special features. Knowledge spillovers and R&D cooperation between some or all of the players involved, for example, will influence strategic efforts in research and development.

Most of the existing studies focus on settings in which firms decide simultaneously on their innovative investments. In the seminal studies of d'Aspremont and Jacquemin (1988) and Kamien et al. (1992), it is shown that, in these simultaneous two stage models, knowledge spillovers discourage competitive R&D efforts and stimulate cooperative R&D choices. Moreover, R&D cooperation results in higher efforts compared to R&D competition provided that the spillover exceeds a critical value[6]. The impact of R&D cooperation on firms' profits, total output and welfare is driven by the same critical spillover value[7].

However, it is well known that innovative firms tend to be heterogeneous and thus may work with different business models and strategies (Röller and Sinclair-Desgagné, 1996), which indicates that R&D decisions may be taken sequentially. After all, some players may attempt to be technological leaders to exploit so called first-mover or lead-time advantages. Others may use a second mover approach and pursue an imitative strategy by relying on their ability to quickly adopt what other firms demonstrate as valuable (Barney, 2002; Schnaars, 1994). Three examples from different industries illustrate this heterogeneity and point to the importance of taking sequential innovative decisions into account.

In the microprocessor industry, which is roughly characterized by a duopoly structure, Intel Corporation has usually been playing the role of technology leader and Advanced Micro Devices (AMD) the role of follower[8]. Especially in the early 1980s, AMD explicitly pursued a strategy of imitation. After all, for the two first product generations, the 8086 and the 80286, AMD waited until Intel released its processors before developing its own products. Worthwhile to mention is the fact that, for these two product generations, AMD had easy access to Intel's technology due to a cross-license agreement with Intel. But despite these high spillovers from Intel to AMD, the latter could only introduce its product a few years later. For example, AMD introduced its version of the 80286 in 1984, two years later than Intel. Since then,

[6] In case of homogeneous products, this critical spillover equals ½. The more products are differentiated, the lower this critical spillover is (De Bondt and Veugelers, 1991)

[7] Overviews of this rich literature are provided by Rosenkranz (1996), De Bondt (1997), Sena (2004) and Motta (2004).

[8] Smaller rivals only have very small market shares, and can be ignored in this illustration.

Intel has continued to be the market leader. Exemplifying Intel's dominant position is its 2006 market share of approximately 73% (Pacheco-de-Almeida and Zemsky, 2008; Business Week (2008); The Economist (1998); The New York Times (2006)).

Another illustration of the heterogeneity of innovative behaviour of firms can be found in the automobile industry and more specifically in the European market for multi-purpose vehicles (MPV's or simply mini-vans). In this market, Renault can be seen as both the technological and market leader. After all, this French automobile constructor was the first to develop an MPV, namely the Espace. Moreover, Renault also marketed its mini-van firstly, in 1985, which clearly resulted in a first mover advantage. Other firms, like Chrysler, Mitsubishi, Nissan, Peugeot, Fiat, Toyota, Volkswagen and Ford can be considered as followers in the European MPV market. Reminiscent of Renault's market leadership is the Espace market share (in the European Community) of more than 20% in 2004. Important to remark is that some followers have been cooperating in R&D in order to try to catch up with Renault. For example, Ford and Volkswagen formed a joint venture (AutoEuropa) and also Peugeot and Fiat combined R&D forces (Sevel) (The New York Times (1990); The New York Times (1993); Commission, 1990).

A third example relates to the dredging industry. In this industry, the four biggest firms, which are De Nul, DEME, Boskalis and Van Oord, control 65% of the market. Smaller firms share the remaining part of the market. Moreover, the big firms are typically leading the innovation process as well. These big firms invest continuously in process innovations, such as the construction of larger ships and the search for the optimal design of the vessels, in order to reduce operating costs. Smaller firms may try to copy some of these innovations (provided that they have sufficient financial resources).

These three examples illustrate that firms do not always take their R&D decisions simultaneously. More specifically, some firms (the technological leaders) move before the other firms (the technological followers) in the R&D process. The market shares of Intel, Renault and the four big dredging companies further indicate that these firms are also the market leaders. Moreover, it is possible that these market leadership positions can persist for a very long time period. To continue, the three examples also point to two other aspects of the R&D process, i.e. the presence of spillovers and the allowance to cooperate in R&D.

After all, an often heard argument to play the role of imitator (technological follower) is the possibility to free ride on the efforts of the innovator. These free riding opportunities are due to the presence of spillovers from the leading to the following firms. For example, AMD enjoyed high spillovers from Intel due to the cross-license agreement. These free riding possibilities or spillovers often make it possible for imitators to duplicate first movers' innovations at a lower cost, even if the leader's innovation is protected by a patent. In the pharmaceutical industry, for example, about 70% of total R&D costs are incurred during the clinical tests. Generic drug manufacturers, the imitators, are however not required to repeat these tests, by which their (imitation) costs are far below the innovator's R&D costs (DiMasi et al., 2003). However, imitators' cost advantages are not always that terribly large. Mansfield et al. (1981) argue that, on average, imitation costs and imitation time are about two thirds of the original development cost and time.

So, it is clear that knowledge flows or spillovers from the leading to the following firms play an important role in the R&D strategies of leaders and followers. These spillovers differ across industries as they depend on the strength of the patent protection of leaders and the ease of reverse engineering, inventing around, learning or duplication. For example, spillovers are typically high in industries like pharmaceuticals and semiconductors while spillovers tend to be of a small or medium level in industries such as machinery and transportation equipment (Bernstein, 1988; Bernstein and Nadiri, 1989; Gruber, 1998).

Moreover, note that in many cases relevant new knowledge can also spill over between leaders and between followers, again through reverse engineering, through contacts with common suppliers or supporting outside laboratories. Changing jobs or employees starting up their own business[9], professional exchanges at conferences and

[9] For example, three former employees of Google founded the new internet search engine Cuil, which was released on July 29th, 2008 (NRC Handelsblad, 2008).

visits[10], and other features likewise may also generate transfers of relevant knowledge. Remark that spillovers may also flow from followers to leaders. The cross-license agreement between Intel and AMD can again be used as an example here. As both firms have access to each other's technology, it is possible that there are also spillovers from AMD to Intel. However, as Intel is the technological leader, it can be expected that the spillover from Intel to AMD is higher than the other way around.

It is probably typical that the heterogeneity between firms implies differences in spillovers. Knowledge spillovers from leaders to followers need not be equal to the spillovers from followers to leaders, as the example of Intel and AMD illustrates. Leaders may also differ in size, technology, absorptive capacity or product portfolio from followers, so that spillovers between leaders need not be the same as spillovers between followers.

Finally, the MPV-case illustrates that firms can cooperate in R&D. Indeed, a widespread phenomenon in the innovation process nowadays is R&D cooperation (Hagedoorn, 2002). Some advantages of combining R&D forces are the avoidance of duplication, easier access to the necessary financial assets and the internalization of the spillovers between the cooperating firms.

In short, the three examples above indicate that it may be interesting to look at the impact of asymmetric spillovers and R&D cooperation when firms decide sequentially on their R&D investments. However, in the literature, the theoretical insights into the spillover effects and the impact of R&D cooperation are, up to now, however strongly biased towards settings with firms choosing their R&D simultaneously in the presence of symmetric spillovers, although a limited set of more recent studies has begun focussing on the implications of firm heterogeneity and asymmetric spillovers.

[10] For example, when Carlos Brito started working for the Brazilian brewery Brahma in 1990, his first assignment was a visit the American brewery Anheuser-Bush. During this visit, Brito learnt how Anheuser-Bush coped with wholesalers, product placement, productivity etc. (De Standaard, 2008).

De Bondt and Henriques (1995), Amir and Wooders (1999) and Amir et al. (2000) look at asymmetric spillovers and role playing in R&D investments in a duopoly with simultaneous output decisions. Halmenschlager (2004) extends this setting to one leader and two followers, but only the latter invest in R&D while Atallah (2005) looks in detail at asymmetric spillovers but in a duopoly with simultaneous moves in R&D investments and output. Goel (1990) looks at only one Stackelberg leader who invests in R&D while followers do not invest in R&D but benefit from the leader's investments via spillovers. Žigič et al. (2006) analyze the persistence of monopoly power using a dynamic duopoly model with one innovating and one imitating firm. Crampes and Langinier (2003) also point to the importance of distinguishing between leading and following firms by comparing their R&D investments in some specific situations.

Note that in related IO literature, some aspects of leader follower behaviour and asymmetric spillovers have already been looked at in earlier contributions. As has been mentioned in the general introduction of this thesis, a lot of research attention has been devoted to the comparison of leader versus follower R&D investments. This literature indicates that role playing affects the incentives in quantity games (Daughety, 1990; Kamien and Zang, 1990) and in innovative races. For example, a leading firm invests less than followers in innovative races with exogenous entry (Reinganum, 1985) while this result is altered when entry is free (Etro, 2004). Moreover, Doraszelski (2003) shows that, in R&D races with knowledge accumulation, a follower, in order to catch up, sometimes invests more than a leader.

The purpose of this chapter is to contribute to the existing literature by analyzing the R&D investment incentives of market leaders and market followers when it is assumed that the former also innovate before the latter. In other words, an industry with one or more persistent dominant firms is considered[11] (e.g. Intel in the microprocessor industry), in which the followers pursue an imitative strategy (e.g. AMD in the microprocessor industry). In addition, symmetric or asymmetric spillovers accompany these sequential R&D decisions and R&D cooperation among leaders or followers is allowed for.

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[11] More dynamic models, in which the leader can be replaced by a follower, are discussed in chapter 3.

Therefore, four stage game settings are modelled with sequential R&D and sequential output decisions (Stackelberg competition) in which the Stackelberg leaders also move before the Stackelberg followers in R&D. The focus hereafter is, however, only on cost-reducing strategic innovative activities. Investment means research and development outlays that produce new knowledge which in turn allows reducing a constant unit variable cost of production. In other words, process innovations are considered[12,13].

The model also allows for spillovers between the different players. More specifically, there are spillovers between the leaders, between the followers, from the leaders to the followers and from the followers to the leaders. As has been explained, these spillovers tend to be asymmetric due to the heterogeneity of leaders and followers. However, symmetric spillovers will also be looked at. This will be done only to compare tendencies with existing symmetric settings. Finally, leaders or followers are also allowed to cooperate in R&D.

So, all in all, a four stage game setting with leading and following firms is looked at with spillovers between the different players and R&D cooperation between leaders or between followers. The following research questions are then tackled. Firstly, it is analyzed whether the impact of the spillovers on the R&D investments of leaders and followers is the same as in the traditional two stage models. After all, R&D investments in a symmetric two stage oligopoly with simultaneous choices are negatively related to the level of spillovers when firms compete in R&D and positively correlated when they cooperate in R&D.

[12] Two examples of process innovations have already shortly been touched upon, i.e. the construction of bigger ships and the search for the optimal design of these ships in the dredging industry. The somewhat narrow approach of only focusing on process innovations yields hopefully the advantage of clarifying the intuition of reported tendencies. At the same time, it allows relating the findings to earlier ones reported in the already abundant literature following the seminal papers of d'Aspremont and Jacquemin (1988) and Kamien et al. (1992).

[13] Ford Motor Company's introduction of the assembly line in the automobile industry serves as a classic but excellent example of a process innovation. By bringing the work to the employees instead of bringing the employees to the work, Henry Ford's ambition was to reduce production time and hence production costs. And indeed, when the first moving assembly line was installed in Highland Park (Detroit) in 1913, the production time for a single car, the Model T, dropped from more than twelve hours to less than six hours (source: www.ford.com, last consulted on June 26, 2008)

Secondly, it is analyzed when technological leapfrogging tends to take place. Technological leapfrogging is here defined as the situation in which each of the followers invests more in R&D than each of the leaders. Special attention is paid to the role played by the spillovers. In addition, it is analyzed whether R&D cooperation can stimulate or discourage technological leapfrogging by followers. Note that this analysis contributes to the longstanding debate in IO about the impact of market structure on R&D incentives as it compares R&D investments of market leaders and market followers.

Thirdly, the impact of R&D cooperation on the investments of leaders and followers is analyzed and tendencies are compared with the two stage settings with simultaneous R&D. In these two stage game settings, R&D cooperation[14] results in higher efforts compared to R&D competition, provided that the symmetric spillover exceeds a critical value.

To continue, next to the analysis of the profitability of leading and following firms, attention is also devoted to the impact of R&D cooperation on welfare. It is important to see whether the allowance for R&D cooperation of leaders or followers can increase consumer and/or total welfare. By doing so, some policy guidelines can be formulated.

The main results are the following. With regard to the impact of spillovers on R&D investments, tendencies can differ from the two stage models. More specifically, the investments of cooperating leaders or cooperating followers can be decreasing with an increasing symmetric spillover level, which is caused by, respectively, the presence of the spillover from leaders to followers and the spillover from the followers to the leaders. Secondly, the model predicts that, if the spillover from the leaders to the followers is sufficiently high, the followers spend more resources on cost-reducing R&D than the leaders. Thirdly, the comparison of competitive and cooperative R&D yields similar results as in the two stage models. Again, critical spillovers drive the tendencies concerning R&D investments, profits and welfare. However, these critical

[14] R&D cooperation as the maximization of joint profits, without increasing the knowledge flows between cooperating firms, is meant.

spillover values are not the same as in the two stage models. Finally, only slight differences between the early and the late entrance setting prevail.

The remainder of this chapter is organized as follows. The model is presented in section 2.2. Section 2.3 deals with the impact of spillovers on R&D efforts. Leader and follower R&D investments are compared in section 2.4. The impact of cooperation of leaders or followers on R&D investments, profits and welfare is discussed in respectively sections 2.5, 2.6 and 2.7. All these tendencies concern the early entrance setting. The late entrance setting is shortly dealt with in section 2.8 and section 2.9 concludes.

2.2. The model

In order to capture the idea of sequential R&D moves by market leaders and market followers, the earlier two stage model with simultaneous moves is extended to a four stage setting with sequential moves (see d'Aspremont and Jacquemin, 1988). More specifically, the focus is on an oligopoly market consisting of n firms competing non-cooperatively on the output market with homogeneous products. Of these n firms, k firms are assumed to be market leaders while the remaining n-k firms are market followers and market leaders move before the followers on the output market (Stackelberg competition). Note that it is assumed that there can be several leaders, which is for example the case in the dredging industry[15]. These market leaders are moreover assumed to move before the market followers in the investment stage[16]. In other words, the leadership role embodies both the R&D as the market side. The assumption of innovative market leaders is based on the three examples mentioned in the introduction. The inverse demand function is:

$$p = a - \sum_{i=1}^{k} q_i^L - \sum_{j=k+1}^{n} q_j^F \ , \qquad (2.1)$$

[15] The introduction of more than one leader is based on the example of the dredging industry. Moreover, it is then possible to analyze the consequences of R&D cooperation among leaders.

[16] In the model here, leading and following roles are determined exogenously. Lieberman and Montgomery (1988) argue that a combination of luck and proficiency (for example technological foresight) could be at the origin of leadership positions. However, as has been explained in the introduction of this chapter, it could be the explicit choice of a firm (for example AMD) to pursue a follower strategy.

with i=1,...,k and j=k+1,...,n. The choke price is a, $\sum_{i=1}^{k} q_i^L$ and $\sum_{j=k+1}^{n} q_j^F$ denote the total output of respectively the leaders (L) and the followers (F). Leaders and followers can commit to strategic investments, respectively x_i^L and x_j^F, in an attempt to maintain or improve the own competitive position. Throughout the paper (and in line with previous literature), these commitments will be equated with cost-reducing R&D investments[17,18].

Two different four stage game settings are considered, i.e. an early entrance and a late entrance setting. In the early entrance setting, the sequence of moves runs as follows. In the first stage, all k leaders decide on their strategic investment levels, knowing that each of the n-k followers will observe their efforts. In the second stage, followers decide on their commitments to innovative efforts. In the third stage, each leader commits to an output level, after observing the investments of the followers, and anticipating the subsequent output choices of the followers. In the final stage, followers decide on their output observing the results of the previous stages. In the late entrance setting, leaders commit to an R&D investment and output level in respectively stage one and stage two before choices of R&D and output of the followers (stage three and stage four). These two settings thus replicate an industry in which market leadership is rather persistent and the market leaders invest in cost-reducing R&D before the market followers, which can be seen as small firms (see e.g. the dredging industry). Thus, the model does not allow for followers to become market leaders. From now on, the model description and the analysis focus only on the early entrance setting. In section 2.8, the late entrance setting is (shortly) dealt with.

Spillovers may occur in the investment stages one and two, between respectively the leaders and the followers. There may also be spillovers between the leaders in stage

[17] Other types of commitments are for example branding, quality improvements or demand-enhancing R&D.

[18] Results could as well be applied to advertising efforts aimed at increasing demand. Indeed, advertising efforts may not only increase demand for the investing firm's product as, due to the publicity, the public's awareness of the product category in general may be increased as well, and hence, also demand for rivals' products may be expanded. In that case, a distinction needs to be made between the ex post market size for the leaders (a^L) and the ex post market size for the followers (a^F) in the inverse demand function.

one and between the followers in stage two. This means that four groups of spillovers are looked at:

- leader-specific spillover β_{LL};
- follower-specific spillover β_{FF};
- spillover from leaders to followers β_{LF};
- spillover from followers to leaders β_{FL}.

All spillovers are exogenous and symmetric in each category. Figure 2.1 explains the notation. Asymmetries are thus limited to possible differences between the four mentioned groups. The last group, spillovers from followers to leaders, is only used here to explain the consequences of spillover symmetry. So, in the symmetric spillover case, it is assumed that there is also knowledge spilling over from followers to leaders in order to relate results with previous findings of the two stage models with symmetric spillovers. When spillovers are asymmetric, it is assumed that there is no spillover from the followers to the leaders, which is not only simplifying the analysis but is also in line with existing theoretical (Amir and Wooders, 1999; Amir et al., 2000) and empirical work (Knott et al., 2004).

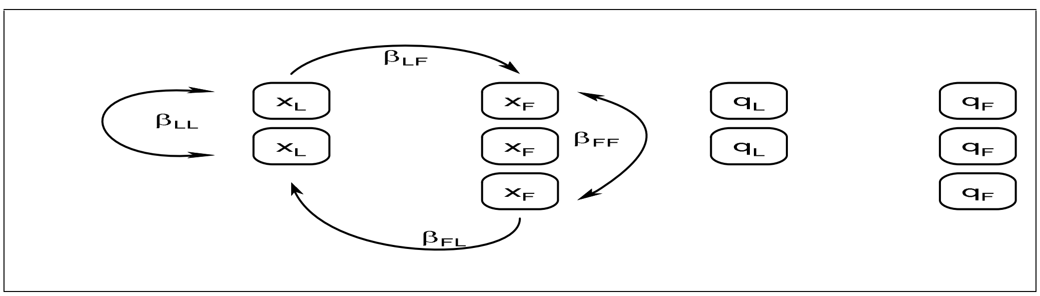

Figure 2.1. The early entrance setting for k=2 and n=5. Extension to the general case of $1 \leq k<n$ is obvious. The spillover from followers to leaders β_{FL} is set equal to zero, except in the benchmark case of symmetric spillovers.

In modern market economies spillovers will depend on the type of strategic investments, as well as on the industry and the cultural, economic and legal environment. Some polar cases that will receive attention are blue print copying (β_{LF}=1) and idea diffusion (β_{LF}=0). In reality, spillovers (nearly) always lie between these two extremes, which are nevertheless very useful as benchmarks. The terminology serves as a metaphor and is borrowed from technology diffusion studies

Blue print copying takes place when the followers have access to very detailed information, a blue print, on how the new product or new process has been developed. Blue print copying may take place when patent protection is not effective and when knowledge developed by leaders is a pure public good. An example stems from the already described microprocessor industry in the early 1980s when AMD enjoyed high spillovers from Intel due to a cross-licensing agreement (see also section 2.1). The wheel servers as another example of blue print copying as it was presumably easy to copy it just by looking at it.

With idea diffusion, the followers are only aware of the basic idea of the innovative product as the leaders are able to completely appropriate their knowledge because of, for example, perfect patent protection, the absence of the possibility to conduct reverse engineering, different suppliers of inputs, little job rotation between firms, the lack of close professional contacts, etc. In this case followers only learn that it is possible to improve on production technologies and observe investment levels of leaders. Their R&D moves have therefore to follow those of the leaders. An example of idea diffusion is the production of porcelain, which was reinvented around 1700 in Europe, given the Chinese examples from the 7th century that reached the West in the 14th century. The German follower alchemist Johann Friedrich Böttger only knew for certain that it could be done and thus faced idea diffusion (Diamond, 1997)[19].

All firms enter stage one or two with an ex ante unit cost equal to c. The leaders enter stage three with an ex post unit cost c_i^L. The followers enter stage four with an ex post unit cost c_j^F. Both ex post values are the difference between the ex ante unit costs and the amount of effective knowledge that the player has accumulated in the previous stages. The effective value is the sum of the own efforts and the imported knowledge from other firms that results from the spillovers and equals a cost-reduction of that

[19] Note that it is sometimes not clear whether idea diffusion or blue print copying is at work. For example, some scientists argue that the Russian construction of the atomic bomb was based on a blueprint of the existing American A-bomb because of information transmissions by spies. Others believe that the Russians were only aware of the feasibility of constructing an A-bomb, due to the bombing of Hiroshima, and they reinvented the A-bomb with little information from Americans (Diamond, 1997).

amount expressed in for example dollars. The ex post unit costs of leaders and followers are therefore given by the following equations (2.2) and (2.3):

$$c_i^L = c - \left(x_i^L + \beta_{LL} \sum_{\substack{l=1 \\ l \neq i}}^{k} x_l^L + \beta_{FL} \sum_{f=k+1}^{n} x_f^F \right) \qquad i=1,...,k \text{ and} \tag{2.2}$$

$$c_j^F = c - \left(x_j^F + \beta_{FF} \sum_{\substack{f=k+1 \\ f \neq j}}^{n} x_f^F + \beta_{LF} \sum_{l=1}^{k} x_l^L \right) \qquad j=k+1,...,n. \tag{2.3}$$

On the basis of these ex post unit costs, a Stackelberg equilibrium is obtained in stages three and four. The equilibrium output levels depend, given (2.2) and (2.3), on the investments to be made in the earlier stages. These investments have for all firms a cost $g(x)$ with diminishing returns:

$$g\left(x\right) = \frac{\tau}{2} x^2 \text{ with } \tau \text{ a given parameter and } \tau > 0. \tag{2.4}$$

There is no discounting. Leaders' and followers' profit functions are given by respectively (2.5) and (2.6):

$$\pi_i^L = \left(p - c_i^L\right) q_i^L - g\left(x_i^L\right) \qquad i=1,...,k \text{ and} \tag{2.5}$$

$$\pi_j^F = \left(p - c_j^F\right) q_j^F - g\left(x_j^F\right) \qquad j=k+1,...,n \tag{2.6}$$

with q_i^L and q_j^F the Stackelberg equilibrium values of the last stages. The followers choose their investments in stage two and the leaders choose in stage one, knowing the effect on the rest of the game.

Note that it is thus assumed that leading and following firms are ex ante symmetric. It could of course be argued that the leaders could have lower initial unit costs (lower c) and/or face a more efficient R&D cost function (lower τ). However, in the analysis here, these potential asymmetries are not taken into account. The reason is that the main purpose of this chapter is the analysis of the role of symmetric and asymmetric spillovers. Introducing ex ante asymmetry between leaders and followers, in terms of different ex ante unit costs and/or asymmetric R&D cost functions, would only complicate the analysis and divert attention from the role of the spillovers[20].

The output choices of the leaders in stage three and of followers in stage four are always simultaneous Cournot-Nash strategies within each group and stage. Leaders may compete in R&D with other leaders, and likewise for the followers. This game is labelled somewhat loosely the R&D competition game (indicated by (N,N)) as there is both competition of leaders and followers in R&D (Nash behaviour in R&D)**.** Note that R&D competition refers to simultaneous competitive R&D choices within the group of leaders and followers in respectively the first and second stage of the game.

However, leaders and followers can also cooperate in R&D[21]. Two related forms of R&D cooperation are considered here, namely (using both the notation and the terminology of Kamien et al. (1992)) R&D cartelization (labelled by C) and Research Joint Venture (RJV) cartelization (labelled by CJ). In an R&D cartel, the cooperating firms only coordinate their R&D activities. Mathematically, this is captured by the maximization of the joint profits of the R&D cartel members. In an RJV cartel, the cooperating firms not only coordinate their R&D strategies but, moreover, they enhance the knowledge sharing among member firms. It is assumed that, in case of RJV cartelization, the spillover among the cooperating firms is equal to the maximum value of 1 [22].

Cooperation among all leaders but not among followers is looked at, while also cooperation among all followers but not among leaders is analyzed. One may think of situations where leaders and followers are operating in different geographic regions or business cultures. They may also face different discounting of the future so that cooperation is sustainable for one group but not necessarily for the other (Kesteloot and Veugelers, 1995).

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[20] Where possible, some implications of ex ante asymmetric unit costs will be shortly dealt with.
[21] It is assumed that cooperation in R&D never results in collusion on the output market, although R&D cooperation makes it more likely that firms collude on the product market (Martin,1995; Suetens, 2008).
[22] The situation in which firms do not coordinate their R&D activities but only maximize the knowledge sharing (labelled RJV competition by Kamien et al. (1992)), is not covered here in order to avoid an overload of results.

Consequently, five different games emerge. Besides the R&D competition game (N,N), there are two games with cooperating leaders and competing followers, i.e. game (C,N) with R&D cartelization among the leaders and game (CJ,N) with RJV cartelization among the first movers. Analogically, the games where leaders compete among each other in stage one and followers cooperate in stage two are indicated by (N,C) when followers form an R&D cartel and (N,CJ) when followers create an RJV cartel. Table 2.1 summarizes these five possible games.

Choice of R&D investment / Game	By leaders vis-à-vis other leaders	By followers vis-à-vis other followers
(N,N)	Nash	Nash
(C,N)	R&D cartel	Nash
(N,C)	Nash	R&D cartel
(CJ,N)	RJV cartel	Nash
(N,CJ)	Nash	RJV cartel

Table 2.1. Five possible games dependent on the behaviour of leaders and followers in the R&D stages (R&D competition, R&D cartelization or RJV cartelization) in the early entrance setting. In all games, a Stackelberg equilibrium in output is anticipated in stages three and four.

As has been mentioned before, both symmetric and asymmetric spillovers are looked at. For reasons of clarity, Table 2.2 provides a detailed description of spillover symmetry and asymmetry in each of the five games. With asymmetric spillovers, there is no knowledge flow from followers to leaders.

	Symmetric spillovers	Asymmetric spillovers
(N,N), (C,N), and (N,C)	$\beta_{LL}=\beta_{LF}=\beta_{FF}=\beta_{FL}=\beta$	$\beta_{LL}\neq\beta_{LF}\neq\beta_{FF}$ and $\beta_{FL}=0$
(CJ,N)	$\beta_{LF}=\beta_{FF}=\beta_{FL}=\beta$ and $\beta_{LL}=1$	$\beta_{LF}\neq\beta_{FF}$, $\beta_{LL}=1$ and $\beta_{FL}=0$
(N,CJ)	$\beta_{LL}=\beta_{LF}=\beta_{FL}=\beta$ and $\beta_{FF}=1$	$\beta_{LL}\neq\beta_{LF}$, $\beta_{FF}=1$ and $\beta_{FL}=0$

Table 2.2. Definition of symmetric and asymmetric spillovers in the five games in the early entrance setting.

All games are solved by backward induction. However, the solutions for the optimal investment levels and consequent output and profit levels of leaders and followers are rather complex. The analysis and results were therefore obtained by executing numerous numerical simulations. Throughout the remainder of this chapter, simulations have been conducted for the following parameter values: n=10, a=1000, c=100 and τ=400 but tendencies are robust for other parameter values. When possible, analytical solutions are presented.

2.3. The impact of spillovers on R&D investments

In the two stage models with simultaneous moves, competitive choices of R&D tend to be discouraged by larger symmetric spillovers, while cooperative choices in an R&D cartel tend to be stimulated by symmetric transfers (see e.g. D'Aspremont and Jacquemin, 1988; Kamien et al., 1992; De Bondt, 1997). Generally, these tendencies appear as well in the leader follower model considered here, although some interesting variations apply.

In this section, it is useful to first have a look at the impact of asymmetric spillovers before moving to the analysis of the impact of symmetric spillovers. The reason is that a change in the symmetric spillover β boils down to an equal change in each of the four asymmetric spillovers.

2.3.1. Asymmetric spillovers

If all spillovers are different, it is possible to investigate the effect of changing one spillover at the time. The tendencies describing the impact of the different spillovers on the innovative efforts of leaders and followers are formalized in Propositions 2.1.a, 2.1.b and 2.1.c. Note that, as has been mentioned in section 2.2, it is assumed that there is no spillover from the followers to the leaders when dealing with asymmetric spillovers.

Proposition 2.1.a. Assume that, in the early entrance setting, leaders learn nothing from followers (β_{FL}=0). An increase in the leader-specific spillover β_{LL} among leaders will:

- discourage R&D of competing leaders in games (N,N), (N,C) and (N,CJ);
- stimulate R&D by cooperating leaders in an R&D cartel (game (C,N));
- have no impact on R&D of cooperating leaders in an RJV cartel (game (CJ,N));

- have no impact on R&D of followers in game (CJ,N);
- have ambiguous effects on R&D of followers in games (N,N), (C,N), (N,C) and (N,CJ).

Proposition 2.1.b. Assume that, in the early entrance setting, leaders learn nothing from followers (β_{FL}=0). An increase in the follower-specific spillover β_{FF} among followers will:

- discourage R&D of competing followers in games (N,N), (C,N) and (CJ,N);
- stimulate R&D by cooperating followers in an R&D cartel (game (N,C));
- have no impact on R&D of cooperating followers in an RJV cartel (game (N,CJ));
- have no impact on R&D of leaders in game (N,CJ);
- have ambiguous effects on R&D of leaders in games (N,N), (C,N), (N,C) and (CJ,N).

Proposition 2.1.c. Assume that, in the early entrance setting, leaders learn nothing from followers (β_{FL}=0). An increase in the one-way outgoing spillover β_{LF} from leaders to followers tends to:

- discourage R&D of leaders (in all games);
- have ambiguous effects on R&D of followers (in all games).

The impact of the leader-specific and follower-specific spillovers is clearly in line with the findings of the earlier two stage models. When leaders compete in R&D, their investments are negatively related to β_{LL}, which corresponds to the traditional appropriability or free riding effect. However, when leaders cooperate in an R&D cartel, they also take into account the impact of their investments on the rival firms' profits. Consequently, investments of R&D cartelized leaders are increasing in the leader-specific spillover. After all, when the leader-specific spillover is small, an investment of one leader negatively affects other leaders' profits, by which the investing leader in an R&D cartel will reduce its efforts. With a large leader-specific spillover, the reverse is true. The third and fourth claim of Proposition 2.1.a are trivial as β_{LL} equals 1 when leaders form an RJV cartel. Finally, the impact of β_{LL} on followers' R&D investments can be positive or negative, but it should be stressed that these changes are very small and almost negligible. An analogous logic applies to the impact of the follower-specific spillover β_{FF} on investments of leaders and followers (see Proposition 2.1.b).

Finally, the spillover from the leaders to the followers β_{LF} reduces the appropriability of the advantages of the innovative efforts of the leaders by which their incentives are lowered. This tendency occurs in every game as leaders never cooperate in R&D with followers. This generalizes the finding that one-way spillovers from an innovator to an imitator tend to discourage the efforts of the former (as found by Amir and Wooders (1999)). In a simple setting with one leader and one follower, the follower is stimulated by such an increase in received knowledge, but the reverse tendency is also possible[23].

2.3.2. Symmetric spillovers

Keeping in mind the impact of the asymmetric spillovers, it is now easier to understand the impact of a change in the symmetric spillovers on the investments of leaders and followers. Once again, it should be noticed that the case of symmetric spillovers is somewhat exceptional in the present setting. After all, with two groups of players, the underlying heterogeneity of leaders and followers will typically result in some asymmetries in the possibilities for transferring knowledge within or between the groups.

In this section, we start by describing tendencies when there are still some asymmetries in spillovers. Firstly, in Proposition 2.2, it is assumed that $\beta_{LL}=\beta_{FF}$, $\beta_{LF}=0$ and $\beta_{FL}=0$. To continue, in Proposition 2.3, the symmetry is extended to the spillover from the leaders to the followers, i.e. $\beta_{LL}=\beta_{FF}=\beta_{LF}$ and $\beta_{FL}=0$. Finally, the impact of the fully symmetric spillover is described ($\beta_{LL}=\beta_{FF}=\beta_{LF}=\beta_{FL}$). Gradually moving from full asymmetry (section 2.3.1) to full symmetry contributes to a better understanding of the impact of the fully symmetric spillovers.

[23] Although it is assumed that there is no spillover from followers to leaders when considering asymmetric spillovers, it is useful to shortly describe the impact of β_{FL} on R&D investments of leaders and followers as this information is useful when dealing with symmetric spillovers. Followers are discouraged by an increase in β_{FL} while investments of leaders can be both encouraged or discouraged by β_{FL}, but these effects are again very small and can (almost) be ignored.

Proposition 2.2. Assume that, in the early entrance setting, leaders learn nothing from followers (β_{FL}=0), followers learn nothing from leaders (β_{LF}=0) and $\beta^{\circ\circ}=\beta_{LL}=\beta_{FF}$ in games (N,N), (C,N) and (N,C). An increase in this symmetric group specific spillover $\beta^{\circ\circ}$ will:

- discourage R&D of competing leaders (in games (N,N) and (N,C)) and competing followers (games (N,N) and (C,N));
- stimulate R&D by cooperating leaders in an R&D cartel (game (C,N));
- stimulate R&D by cooperating followers in an R&D cartel (game (N,C)).

The propositions of the previous section make it easy to understand the tendencies described in Proposition 2.2. From Proposition 2.1.a, it is known that an increase in the leader-specific spillover β_{LL} reduces the R&D investments of competing leaders. Moreover, see Proposition 2.1.b, an increase in the follower-specific spillover β_{FF} has ambiguous effects on the innovative efforts of the leading firm. However, the latter effects are so small that the negative effect of the leader-specific spillover always dominates. Consequently, R&D investments of competing leaders are decreasing in $\beta^{\circ\circ}$. Analogous argumentations explain the other tendencies of Proposition 2.2.

Note that in proposition 2.2, tendencies of R&D investments of leaders and followers in games (CJ,N) and (N,CJ) are ignored. After all, in game (CJ,N) for example, it is known that β_{LL}=1 and if $\beta_{LF}=\beta_{FL}$=0, only the impact of β_{FF} on R&D investments of leaders is looked at, an analysis which has been described in the previous section 2.3.1.

Allowing for some more symmetry in spillovers yields more complicated tendencies, which are formalized in Proposition 2.3.

Proposition 2.3. Assume that, in the early entrance setting, leaders learn nothing from followers (β_{FL}=0) and assume $\beta^{\circ}=\beta_{LF}=\beta_{LL}=\beta_{FF}$ in games (N,N), (C,N), (N,C); $\beta^{\circ}=\beta_{LF}=\beta_{FF}$ in game (CJ,N) and $\beta^{\circ}=\beta_{LF}=\beta_{LL}$ in game (N,CJ). An increase in this symmetric spillover β° will:

- discourage R&D of competing leaders and competing followers in game (N,N);

- discourage R&D of leaders if the number of leaders is small ($k \leq n/2$) or stimulate R&D of leaders if the number of leaders is large ($k > n/2$) and discourage R&D of followers in game (C,N);
- discourage R&D of leaders and stimulate R&D by followers in game (N,C);
- discourage R&D of leaders and discourage or stimulate R&D by followers in game (CJ,N);
- discourage R&D of leaders and stimulate R&D by followers in game (N,CJ).

The propositions of the previous section contribute again to a better understanding of Proposition 2.2. These tendencies are almost the same as the ones that appear in symmetric oligopolies with simultaneous choices of R&D preceding Cournot-Nash rivalry. For example, the investments of cooperating followers in an R&D cartel are positively related with the spillover. Indeed, the positive effect of an increase in β_{FF} on investments of followers in an R&D cartel outweighs or reinforces the small positive or negative effect of the changes in β_{LL} and β_{LF}.

However, an important difference with the two stage models occurs when leaders cooperate in an R&D cartel (game (C,N)), as mentioned in the second claim of Proposition 2.3. The spillover $\beta°$ may discourage efforts of a small number of cooperating leaders in an R&D cartel or encourage investments when a large number of leaders cooperates in an R&D cartel. From the previous section (2.3.1), it is known that a change in $\beta°$ embodies three effects:

- an increase in the leader-specific spillover (β_{LL}) that stimulates cooperating leaders' efforts in an R&D cartel (see Proposition 2.1.a),
- an increase in the follower-specific spillover (β_{FF}) that can have a very small positive or negative effect on leader's efforts (see Proposition 2.1.b),
- an increase in leakage from the leaders to the followers (β_{LF}) that discourages leaders' efforts (see Proposition 2.1.c).

When the number of leaders is small, the negative effect of β_{LF} dominates the positive effect of β_{LL}, yielding a negative relation with the spillover $\beta°$ (the impact of the change in the follower-specific spillover is very small and can be ignored). In other words, free riding opportunities by a large group of followers frighten a small R&D cartel of leaders. However, when al lot of leaders cooperate in an R&D cartel, the positive effect due to the cooperation dominates the negative effect resulting from the free riding opportunities by the followers.

Finally, the impact of the fully symmetric spillover (β=β_{LL}=β_{FF}=β_{LF}=β_{FL}) is looked at. The findings are summarized in Proposition 2.4.

Proposition 2.4. Assume that, in the early entrance setting, leaders learn nothing from followers (β_{FL}=0) and assume (β=β_{LL}=β_{FF}=β_{LF}=β_{FL}) in games (N,N), (C,N), (N,C); β=β_{FF}=β_{LF}=β_{FL} in game (CJ,N) and (β=β_{LL}=β_{LF}=β_{FL}) in game (N,CJ). An increase in this symmetric spillover β will always discourage R&D investments of leaders and followers. Only when a large number of leaders cooperates in an R&D cartel (k>n/2), their investments are stimulated by an increase in the symmetric spillovers.

As can been observed in Proposition 2.4, leaders' and followers' R&D investments are always negatively related to the fully symmetric spillover. Even the investments of R&D cartelized followers can no longer be stimulated by an increase in the fully symmetric spillover, as was the case in the simultaneous two stage games. This negative relation is due to the negative impact of the spillover from the followers to the leaders (see footnote 23) which always dominates the positive impact of the spillover among the cooperating followers. Also efforts of R&D cartelized leaders are decreasing in the fully symmetric spillover, as long as the number of leaders is not too large. When a lot of leaders form an R&D cartel, their investments are encouraged by an increase in the symmetric spillover. The reasoning is similar as for Proposition 2.3. It thus turns out that the impact of the symmetric spillovers on R&D investments of leaders and followers can be different than in the simultaneous two stage games.

2.4. Impact of leading or following on R&D investments

In some industries, industry leaders can maintain their leadership position for several decades. Intel Corporation, for example, has been the leader in the microprocessor industry for several decades. This persistence of leadership can often be explained by leaders' large investments in R&D. In 1995, for example, Intel devoted $1,3 billion to R&D, corresponding to an R&D intensity[24] of approximately 8% (Segerstrom and

[24] R&D intensity here is equal to the R&D expenditures divided by sales.

Zolnierek, 1999). One explanation for these high investments could be that leaders may be able to improve more easily on own products than smaller firms (Segerstrom and Zolnierek, 1999). Malerba and Orsenigo (1999) provide further evidence on the intense R&D activity by market leaders. Based on EU patent data, they show that, in general, a significant part of total innovative activity can be attributed to some large and persistent innovators.

However, in other industries, incumbent established firms fail to remain technological leaders. A number of factors can contribute to this tendency for innovative performance to slow down, related to for example the fear of cannibalization of current winning product lines, the sunk nature of an existing technology and the inappropriate evaluation of innovative ventures (Schnaars, 1994). Failures of firms to remain the leader can also be the result of a shortage of financial or technological resources or managerial lethargy. For example, cotton-spinners just lacked financial and technological resources when DuPont came up with synthetic fibers in the first half of the 20th century (Christensen and Bower, 1996).

Economists have detected in racing and other models that the disincentives to invest in R&D are caused by high current profits and have called this the replacement effect (Arrow, 1962). Newcomers are not inhibited by this desire to protect current success and have strong incentives to engage in larger innovative efforts to introduce new products or superior imitations that hurt leaders' profits. Empirical tendencies in some very large samples have detected that the lower efforts of the incumbent and the larger efforts of the challengers seem to prevail on average (Czarnitzki and Kraft, 2004).

In some markets, all of this may result in so called technological leapfrogging, which corresponds to the situation in which an initial technological follower has access to a better technology than the leader. Moreover, in the end, this may result in the follower surpassing the leader. This happened for example in the video game console industry (Schilling, 2003) and in the industry for computerized ticketing services (Schnaars, 2004). In 1980, the technological and market leader in this latter industry was Ticketron, which at that time had enjoyed a leadership position for a period of about twelve years. At that moment in time, no one (and certainly not the management of Ticketron) could imagine that this hegemony would end one day. However, Ticketmaster, after having survived financial difficulties in the late 1970s, improved on Ticketron's system by heavily investing in R&D. One of the major improvements was the integration of the accounting function of its customers (for example concert halls). Ticketron was unwilling to respond to and to invest in these improvements, which, in combination with Ticketmaster's large innovative efforts, resulted in the technological and, somewhat later, the market lead of Ticketmaster (Schnaars, 1994). Followers that surpass pioneers may thus engage in more intensive innovative efforts.

This section contributes to a better understanding of this process of technological leapfrogging by shedding light on the role played by free riding opportunities in this process. Here, technological leapfrogging is defined as the situation in which each follower invests more than each leader[25]. Moreover, it will be analyzed whether R&D cooperation among leaders or followers enhances or discourages technological leapfrogging. It should be noted that technological leapfrogging here does not imply that followers become the market leaders as the sequence of play on the market is determined exogenously (static character of the game[26]). Nevertheless, the analysis here might provide useful insights into the role of spillovers in the process of technological leapfrogging. The findings here, both with symmetric and asymmetric spillovers, are again extracted from numerical simulations.

2.4.1. Symmetric spillovers

With symmetric spillovers, comparing leaders' and followers' efforts yields Proposition 2.5.

Proposition 2.5. With symmetric spillovers ($\beta=\beta_{LL}=\beta_{LF}=\beta_{FF}=\beta_{FL}$), leaders generally invest more than followers in the early entrance setting. Followers only invest more than leaders when

- a large number of leaders cooperate in an R&D cartel and the symmetric spillover is small (game (C,N)) or

[25] Note that technological leapfrogging could also be defined as the situation in which the followers have lower ex post unit costs than the leaders. In other words, technological leapfrogging would then be equal to the situation in which the followers have larger effective knowledge stocks compared to the leaders. Although this is an interesting research question, the analysis here is limited to the comparison of leaders' and followers' individual efforts. After all, it is then also possible to contribute to the vast literature on the impact of market power (leader or follower) on innovative investments.

[26] In chapter 3, models are analyzed in which an entrant becomes the market leaders in case of leapfrogging.

- a large number followers cooperate in an RJV cartel and the spillover is small (game (N,CJ)).

According to Proposition 2.5, persistence of technological leadership tends to be the rule when spillovers are symmetric. Proposition 2.4 may help to understand the observed tendencies. When both leaders and followers compete, for example, their investments are reduced by the spillover. However, the reduction in the investments of the leaders is never large enough to allow for technological leapfrogging by the followers.

However, technological leapfrogging might sometimes take place when the spillover is symmetric. Firstly, when a large number of leaders cooperates in an R&D cartel (game (C,N)), it is known that a reduction in the symmetric spillover reduces leaders' investments but stimulates followers' R&D efforts (see Proposition 2.4). When the symmetric spillover is now sufficiently small, followers' investments may exceed the efforts of the leaders, and technological leapfrogging takes place.

Furthermore, when a large number of followers form an RJV cartel (game (N,CJ)), their investments can exceed leaders' efforts when the spillover is small. Proposition 2.4 claims that a reduction in the symmetric spillover stimulates both leaders' and followers' investments. However, due to the maximum spillover among the followers, leaders' investments are smaller than the investments of the followers.

Tendencies described in Proposition 2.5 can be observed, in a more general interpretation of strategic investments, in industries in which competing leading firms are using different strategies and business models compared to smaller fringe firms. In the beer sector, for example, large multinational players focus on global advertising and intensive branding, while smaller ones rely on local specialized beer with little or no advertising efforts. Spillovers of goodwill and specific knowledge from one player to the other tend to be rather low and thus a scenario with a (small) symmetric spillover scenario applies. However, when a lot of leaders were then to cooperate in an R&D cartel, followers would realize higher investments. A similar argument could be made for industries with symmetric but high information flows between all players, such as the dredging industry. In this industry, the R&D intensity (R&D

expenditures divided by sales) of the four major players, being Jan De Nul Group, DEME, Van Oord and Royal Boskalis Westminster is around 20% while R&D intensity of smaller firm is around 10%.

2.4.2. Asymmetric spillovers

As Proposition 2.6 details, sharper differences are detected with asymmetric spillovers. However, these tendencies are somewhat complicated. The comparison between leader and follower efforts is mainly driven by the magnitude of the free riding opportunities of the followers (the spillover from the leaders to the followers, β_{LF}). Moreover, R&D cooperation also affects the comparison of leader and follower efforts.

Proposition 2.6. In all games, leaders tend to invest more than followers when the spillover from the leaders to the followers is sufficiently small. However, larger free riding opportunities for the followers increase the likelihood that followers invest more than leaders. The threshold value of the spillover from leaders to followers depends moreover heavily on the cooperative behaviour of leaders and followers.

The crucial role played by the spillover from the leaders to the followers can be understood by considering Proposition 2.1.c., in which it is stated that an increase in the spillover from the leaders to the followers reduces leaders' investment incentives. When these free riding opportunities are too large, investments of leaders can be that much reduced by which followers invest more in R&D than leaders.

In other words, for each game ϕ in the early entrance setting with β_{FL}=0, there exists, given the number of firms and the number of leaders and given values for β_{LL} and β_{FF}, a critical $\beta_{LF}^{e}[\phi]$, which is called the equalizer spillover, for which the following applies, with ϕ indicating the game being played ((N,N), (C,N), (N,C), (CJ,N), (N,CJ)):

- if $\beta_{LF}<\beta_{LF}^{e}[\phi]$ then $x^{L}[\phi]>x^{F}[\phi]$;
- if $\beta_{LF}=\beta_{LF}^{e}[\phi]$ then $x^{L}[\phi]=x^{F}[\phi]$;
- if $\beta_{LF}>\beta_{LF}^{e}[\phi]$ then $x^{L}[\phi]<x^{F}[\phi]$.

In Tables 2.3a, 2.3b and 2.3a, some numerical examples of the equalizer spillover $\beta_{LF}^{e}[\phi]$ are provided. Note that when $\beta_{LF}^{e}>1$, the investments of the leaders are always higher than the investments of the followers. Analogously, when $\beta_{LF}^{e}<0$, the followers always invest more than the leaders[27].

It is best to first have a look at the game with competing leaders and competing followers (game (N,N)). The numerical simulations of the level of the equalizer spillover indicate that, when there is a small leader-specific spillover, leaders are likely to invest more than followers (game (N,N)). However, when the leaders face both a high leader-specific spillover and a high outgoing spillover to the followers, leaders may be that much discouraged to invest in R&D (as there is both free riding by the other leaders and by the followers), by which the followers may end up with the largest R&D efforts.

Managing spillovers can be a first tool for leaders to discourage technological leapfrogging. Leaders could try to minimize the outgoing spillover to the followers in order to avoid technological leapfrogging by the followers. One obvious way to lower the outgoing spillover is the retention of R&D employees (Gersbach and Schmutzler, 2003). Furthermore, managers could also enforce rules that restrict the transfer of knowledge to only a specified set of employees. Other rules could restrict physical access by employees or visitors to certain locations of the firm, such as laboratories. The decreasing impact of these rules on the outgoing spillover depends of course on management's capabilities to monitor employees' compliance (Liebeskind, 1997).

On the other hand, followers can stimulate the process of technological leapfrogging by maximizing the spillover from the leader to the followers. Therefore, followers could improve their learning capabilities and absorptive capacities by for example investing in basic research (Cohen and Levinthal, 1989; Adams, 2000; Cassiman et al., 2002). In addition, followers could also actively search for R&D employees of the leading firms. For example, when German investment banks (the followers) moved to London in order to establish a stronger position in the sector, they were looking

[27] It should be noticed here that the assumed ex ante asymmetry plays an important role here. Preliminary results indicate that the equalizer spillover increases when leaders have lower ex ante unit costs than the followers by which technological leapfrogging is less likely to occur.

aggressively to hire employees from local competitors (the leaders). The following citation illustrates this:

> *"Last year* [1996]*, Deutsche Morgan Grenfell (DMG), the fast-expanding investment-banking arm of Germany's Deutsche Bank, tormented rivals with raids on their most precious employees, occasionally nabbing whole teams of bankers at a time."* (The Economist, 1997).

A second tool for firms to manage the likelihood of technological leapfrogging is R&D cooperation. However, a careful use of this instrument is recommended. By cooperating in an R&D cartel, the leaders can only increase the equalizer spillover when there is a large spillover among the leaders. Indeed, when β_{LL}=1, the equalizer spillover increases when leaders move from R&D competition (Table 2.3a) to R&D cartelization (Table 2.3b). The reason is that R&D cartelized leaders invest more than R&D competing leaders when there is a large leader-specific spillover (see section 2.5). It should be clear that an RJV cartel among leaders is thus always effective in reducing the likelihood of leapfrogging, as the spillover among the leaders is then equal to 1.

Followers, however, may also use R&D cooperation when they try to catch up with the leaders. When comparing the equalizer spillovers in Tables 2.3a and 2.3c, we observe that technological leapfrogging is more likely when followers, who face a high follower-specific spillover, are cooperating in an R&D cartel instead of competing in the R&D stage. After all, a sufficiently high spillover among followers enhances their efforts (see section 2.5), by which the equalizer spillover is reduced. Finally, forming an RJV cartel always lowers the equalizer spillover, as the follower-specific spillover equals 1 by which technological leapfrogging becomes more likely[28].

In conclusion, it thus turns out that there is a wide set of circumstances in which followers invest more in innovative activities than leaders. The likelihood of

[28] When both leaders and followers would form an R&D cartel, it can be expected that the equalizer spillover would increase when β_{LL}=1 and β_{FF}=0. Analogously, the equalizer spillover is expected to decrease when β_{LL}=0 and β_{FF}=1. However, when β_{LL}=0 and β_{FF}=0 (or β_{LL}=1 and β_{FF}=1), it is a priori hard to predict whether the equalizer spillover would decrease or increase.

technological leapfrogging is positively related to the spillover from the leaders to the followers. In other words, the larger the free riding opportunities are, the more likely it is that followers catch up technologically with the leaders. It has also been indicated that R&D cooperation among leaders (followers) may enhance (reduce) leapfrogging opportunities. Another obvious instrument for leaders to discourage technological leapfrogging is to better protect knowledge. On the contrary, followers can stimulate technological leapfrogging by maximizing the incoming spillover from the leaders.

If there is only one leader and one follower and blue print copying (β_{LF}=1), the model predicts that the follower may invest more than the leader. This tendency is consistent with the familiar case of an imitator surpassing a pioneer. In the pharmaceutical industry, for example, blue print copying could correspond to one firm having a patent on a new drug. The patent may give all the information about the chemical avenues to pursue and inventing around may be stimulated. In 1954, Hoffman-La Roche knew that a competitor had a pill to calm down agitated people. It went on to order extensive pharmaceutical testing that culminated in Librium in 1960 and in Valium in 1963 (The Economist, 2005).

n=10, k=2		β_{FF} = 0	β_{FF} = 1	n=10, k=5		β_{FF} = 0	β_{FF} = 1
β_{LL}	0	$\beta_{LF}^e>1$	$\beta_{LF}^e>1$	β_{LL}	0	$\beta_{LF}^e>1$	$\beta_{LF}^e>1$
	1	$\beta_{LF}^e=0.764$	$\beta_{LF}^e=0.856$		1	$\beta_{LF}^e=0.058$	$\beta_{LF}^e=0.178$

Table 2.3a. Numerical examples (early entrance setting) for the equalizer spillover β_{LF}^e in the game with R&D competition among leaders and R&D competition among followers (game (N,N)). Leaders invest more (less) than followers if and only if $\beta_{LF}<\beta_{LF}^e$ ($\beta_{LF}>\beta_{LF}^e$).

n=10, k=2		β_{FF} = 0	β_{FF} = 1	n=10, k=5		β_{FF} = 0	β_{FF} = 1
β_{LL}	0	$\beta_{LF}^e=0.382$	$\beta_{LF}^e=0.428$	β_{LL}	0	$\beta_{LF}^e=0.007$	$\beta_{LF}^e=0.033$
	1	$\beta_{LF}^e=0.944$	$\beta_{LF}^e=0.988$		1	$\beta_{LF}^e=0.966$	$\beta_{LF}^e=0.988$

Table 2.3b. Numerical examples (early entrance setting) for the equalizer spillover β_{LF}^e in the game with R&D cartelization among leaders and R&D competition among followers (game (C,N)). In the grey cells, the equalizer spillover values for the game with RJV cartelization among leaders and R&D competition among followers (game (CJ,N)) are indicated (β_{LL}=1). Leaders invest more (less) than followers if and only if $\beta_{LF}<\beta_{LF}^e$ ($\beta_{LF}>\beta_{LF}^e$).

n=10 k=2		β_{FF}		n=10 k=5		β_{FF}	
		0	1			0	1
β_{LL}	0	$\beta_{LF}^e>1$	$\beta_{LF}^e<0$	β_{LL}	0	$\beta_{LF}^e>1$	$\beta_{LF}^e=0.205$
	1	$\beta_{LF}^e=0.861$	$\beta_{LF}^e<0$		1	$\beta_{LF}^e=0.183$	$\beta_{LF}^e<0$

Table 2.3c. Numerical examples (early entrance setting) for the equalizer spillover β_{LF}^e in the game with R&D competition among leaders and R&D cartelization among followers (game (N,C)). In the grey cells, the equalizer spillover values for the game with R&D competition among leaders and RJV cartelization among followers (game (N,CJ)) are indicated (β_{FF}=1). Leaders invest more (less) than followers if and only if $\beta_{LF}<\beta_{LF}^e$ ($\beta_{LF}>\beta_{LF}^e$).

2.5. Impact of cooperation on R&D investments

In this section, competitive and cooperative R&D investments of leaders and followers are compared. First, symmetric spillovers are dealt with, followed by the analysis with asymmetric spillovers.

2.5.1. Symmetric spillovers

With symmetric spillovers, comparing R&D investments of leaders and followers under the different modes of R&D behaviour (R&D competition, R&D cartelization and RJV cartelization) yields Proposition 2.7.

Proposition 2.7. With symmetric spillovers in the early entrance setting, the following applies to the R&D investments of the leaders and the followers:

- Leaders always invest most when they form an RJV cartel. When leaders cooperate in an R&D cartel, their investments are larger than with R&D competition if and only if the symmetric spillover exceeds a critical value β^{LC}, with $\beta^{LC}=\dfrac{n-k+1}{n-k+2}$;
- Followers always invest most when they form an RJV cartel. When followers cooperate in an R&D cartel, their investments are larger than with R&D competition if and only if the symmetric spillover exceeds a critical value β^{FC}, with $\beta^{FC}=\dfrac{1}{2}$.

The impact of R&D cooperation on the investments of leaders and followers is analogous to the simultaneous two stage models. R&D cartelization is beneficial for the technological progress of leaders or followers when the symmetric spillover is sufficiently large. Remark that the critical spillover for the leaders is not the same as for the followers. The former, labelled[29] β^{LC}, depends on the number of leaders and followers and differs from the critical spillover that was found in the two stage games with simultaneous moves and homogeneous products. Moreover, this critical spillover β^{LC} is decreasing in the number of leaders and when all firms are leading (n=k), β^{LC} equals ½. After all, this specific scenario reduces the four stage setting to the two stage setting with simultaneous moves, by which the same critical spillover level of ½ is found (as in De Bondt et al., 1992).

In line with the two stage models with simultaneous moves, the comparison of competitive and cooperative investments can be explained by the presence of externalities (see De Bondt and Veugelers, 1991). When leaders compete in R&D and the symmetric spillover is smaller (larger) than β^{LC}, the R&D investment of a certain leader causes a negative (positive) externality on the other leaders. Consequently, when $\beta<\beta^{LC}$ ($\beta>\beta^{LC}$), the investing leader has an incentive to overinvest (underinvest). When leaders cooperate in an R&D cartel, these externalities are internalized by which cooperative investments of leaders in an R&D cartel are lower than competitive R&D investments when the spillover is smaller than β^{LC} and cooperative investments in an R&D cartel exceed competitive investments when the spillover is larger than β^{LC}. When leaders cooperate in an RJV cartel, their R&D investments are always higher compared to R&D competition due to the maximum spillover among the leaders. An analogous reasoning applies to the comparison of investments of competing versus cooperating followers.

Thus, when leaders or followers want to increase their R&D activities in their quest for low unit costs, R&D cartelization might be an efficient instrument, provided that the spillover is sufficiently large. Furthermore, Proposition 2.7 also indicates that an RJV cartel always yields higher R&D investments compared to R&D competition. This latter tendency suggests that, no matter what the initial spillover level is, leaders (followers) can always improve their technological position by cooperating in an RJV

[29] β^{LC} stands for the critical (C) symmetric spillover for which investments of leaders (L) are the same with R&D competition and R&D cartelization. β^{FC} stands for the critical (C) symmetric spillover for which investments of followers (F) are the same with R&D competition and R&D cartelization.

cartel because of the perfect knowledge sharing among cooperating leaders (followers) in an RJV cartel.

However, some caution is called for here as it is assumed in this study that in an RJV cartel, knowledge is shared to a maximum degree. But, while it is indeed reasonable to assume that firms may sometimes fully share their R&D knowledge (for example through licensing for free), there are several reasons why information sharing may not be perfect in RJV cartels. De Bondt and Wu (1997), for example, argue that the increase in information sharing among cooperating firms may be imperfect due to technical difficulties or differences in organizational culture. It could also be the case that R&D cooperating firms are reluctant to contribute their best R&D personnel to the RJV cartel because they do not want to restrict possibilities for growth in related areas (Shapiro and Willig, 1990; Bhattacharya et al., 1992)

2.5.2. Asymmetric spillovers

With asymmetric spillovers, the comparisons of competitive and cooperative R&D investments of leaders and followers are again driven by critical spillovers, see Proposition 2.8[30].

Proposition 2.8. Assume that, in the early entrance setting, spillovers are asymmetric and suppose leaders learn nothing from followers (β_{FL}=0). Then the following applies to the R&D investments of leaders and followers:

- Leaders always invest most when they form an RJV cartel. When leaders cooperate in an R&D cartel, their investments are larger than with R&D competition if and only if the leader-specific spillover exceeds a critical value β_{LL}^{C}.
- Followers always invest most when they form an RJV cartel. When followers cooperate in an R&D cartel, their investments are larger than with R&D competition if and only if the follower-specific spillover exceeds a critical value β_{FF}^{C}.

[30] $\beta_{LL}{}^{C}$ stands for the critical (C) leader-specific spillover for which investments of leaders are the same with R&D competition and R&D cartelization. $\beta_{FF}{}^{C}$ stands for the critical (C) follower-specific spillover for which investments of followers are the same with R&D competition and R&D cartelization.

Tendencies are again similar to the simultaneous two stage games and also to the leader follower setting with symmetric spillovers. The expressions for the critical spillovers, however, are now rather complicated functions of the other parameters of the model. The critical spillover levels for the leaders (β_{LL}^{C}) and the followers (β_{FF}^{C})[31] depend on the number of leaders and followers, but β_{LL}^{C} is also dependent on the spillover from leaders to followers and the follower-specific spillover. In order to give the reader some feeling about the level of these critical spillovers, Tables 2.4a and 2.4b provide some numerical examples of β_{LL}^{C}, given values for the other parameters of the model.

n=10		β_{FF}	
k=2		0	1
	0	β_{LL}^{C} =0.499	β_{LL}^{C} =0.494
β_{LF}	1	β_{LL}^{C} =0.944	β_{LL}^{C} =0.945

n=10		β_{FF}	
k=5		0	1
	0	β_{LL}^{C} =0.499	β_{LL}^{C} =0.495
β_{LF}	1	β_{LL}^{C} =0.917	β_{LL}^{C} =0.917

Table 2.4a. Numerical examples of the critical leader-specific spillover β_{LL}^{C}. R&D cooperation among leaders in an R&D cartel results in higher (lower) investments, compared to R&D competition, if and only if $\beta_{LL}>\beta_{LL}^{C}$ ($\beta_{LL}<\beta_{LL}^{C}$).

n=10		β_{LL}	
k=2		0	1
	0	β_{FF}^{C} =0.05	β_{FF}^{C} =0.05
β_{LF}	1	β_{FF}^{C} =0.05	β_{FF}^{C} =0.05

n=10		β_{LL}	
k=5		0	1
β_{LF}	0	β_{FF}^{C} =0.0313	β_{FF}^{C} =0.0313
	1	β_{FF}^{C} =0.0313	β_{FF}^{C} =0.0313

Table 2.4b. Numerical examples of the critical follower-specific spillover β_{FF}^{C}. R&D cooperation among followers in an R&D cartel results in higher (lower) investments, compared to R&D competition, if and only if $\beta_{FF}>\beta_{FF}^{C}$ ($\beta_{FF}<\beta_{FF}^{C}$).

As can be derived from Table 2.4a, the critical leader-specific spillover β_{LL}^{C} is (slightly) increasing in the number of leaders k when there is idea diffusion from leaders to followers ($\partial\beta_{LL}^{C}/\partial k>0$ for β_{LF}=0) and decreasing in the number of leaders in case of blue print copying from leaders to followers ($\partial\beta_{LL}^{C}/\partial k<0$ for β_{LF}=1). Taking

[31] $\beta_{FF}^{C}=\dfrac{1}{2+(n+1)k-k^{2}}$

these tendencies into account and carefully analyzing the numerical simulations allow stating the first part of Proposition 2.9.

As can be seen in Table 2.4b, the values of the critical follower-specific spillover β_{FF}^{C} are very small. Consequently, R&D cartelization among followers is almost always yielding higher R&D investments than R&D competition. Only when there is no knowledge sharing at all among the followers (β_{FF}=0), R&D competition results in higher investments compared to R&D cartelization among followers. This tendency is formalized in the second part of Proposition 2.9. Moreover, differentiating reveals that sign [$\partial\beta_{FF}^{C}/\partial k$]=sign [$2k-(1+n)$].

Proposition 2.9. Consider the early entrance setting with asymmetric spillovers (β_{FL}=0), then:

- R&D cartelization among leaders is most likely to result in higher R&D investments compared to R&D competition when there are only limited free riding opportunities by the followers (idea diffusion or β_{LF}=0). When the spillovers from leaders to followers is very large (blue print diffusion or β_{LF}=1), only an RJV cartel among the leaders might result in larger efforts compared to R&D competition.
- R&D cartelization among followers always results in higher investments compared to R&D competition, except for very small values of β_{FF}.

Thus, the larger the followers' free riding opportunities on the investments of the leaders are, the less likely it is that R&D cartelization of leaders is beneficial for the technological progress of the leaders. When facing high spillovers to followers, leaders can only improve on their technological position when they form an RJV cartel.

Once again, externalities are the rationale for these results. When there is R&D competition among leaders and values of β_{LL} are small (large), i.e. $\beta_{LL}<\beta_{LL}^{C}$ ($\beta_{LL}>\beta_{LL}^{C}$), investments of one leader create a negative (positive) externality on the other leaders, by which overinvestment (underinvestment) occurs. With R&D

cartelization, the internalization of the externalities leads to Proposition 2.8. An analogous reasoning applies to the followers.

2.6. Impact of cooperation on profitability

R&D cartelization of leaders in game (C,N) or of followers in game (N,C) always result in an increase of profits of the cooperating players, compared to their profits with R&D competition in game (N,N). Consider for example R&D cartelization among leaders[32].

When the symmetric spillover is smaller than β^{LC}, we know that leaders' R&D investments are higher with R&D competition than with R&D cartelization, by which R&D competitive output of leaders also exceeds R&D cartelized output (the larger the cost-reductions are, the more beneficial it is for firms to expand output). However, the resulting increase in R&D competitive output is offset by the larger R&D investments with R&D competition compared to R&D cartelization, by which leaders' profits are higher when they form an R&D cartel than when they compete in R&D. With a large symmetric spillover, i.e. above the critical value β^{LC}, R&D investments of leaders are higher with R&D cartelization than with R&D competition. The resulting higher R&D cooperative output compensates for the larger R&D investments, and R&D cartelized profits are thus higher than with R&D competition. Finally, when the symmetric spillover equals β^{LC}, leaders' profits remain unchanged. The straightforward reason is that for this spillover level, leaders' innovative efforts in an R&D cartel are unchanged compared to R&D competition.

Moreover, when leaders form an RJV cartel (game (CJ,N)), their profits are always higher than with R&D cartelization or R&D competition. Note that, by definition, R&D cartelized profits equal RJV cartelized profits when β=1 with symmetric spillovers.

Analogous reasonings apply to the impact of R&D cooperation with symmetric spillovers on followers' profits and with asymmetric spillovers on the profitability of

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[32] Note that $\pi^L[\phi]=\frac{1}{n-k+1}\left(q^L[\phi]\right)^2-\frac{\tau}{2}\left(x^L[\phi]\right)^2$ and $\pi^F[\phi]=\left(q^F[\phi]\right)^2-\frac{\tau}{2}\left(x^F[\phi]\right)^2$ with ϕ indicating the game being played.

leaders and followers. Moreover, similar results have been obtained in symmetric simultaneous models where profits are always higher with R&D cartelization than with R&D competition and unaffected by R&D cartelization if and only if the symmetric spillover equals ½ (assuming homogeneous products). The same tendencies are thus present in the sequential early entrance setting considered in this chapter, both with symmetric and asymmetric spillovers.

The result that R&D cartelization (and hence RJV cartelization) is raising the profits of cooperating firms is not that surprising. After all, due to the coordination of R&D strategies in an R&D cartel, competition is softened by which profits are higher compared to R&D competition. Consequently, it would thus always be in the interest of leaders (followers) to cooperate in R&D.

However, R&D cooperation also entails some costs and risks which are not taken into account in the model of this study. Firstly, start-up investments of R&D cooperatives can be quite significant. These start-up costs might involve investments in physical assets, such as an R&D laboratory, and negotiation costs (Pisano, 1990; Brockhoff, 1992). Furthermore, the daily managing of the R&D cartel or RJV cartel may give rise to coordination costs, agency costs and costs of monitoring the partner by which R&D cooperative profits are further reduced (Veugelers, 1997; Becker and Dietz, 2004). Due to these additional costs, cooperation in R&D can fail or simply not take place.

2.7. Implications for welfare

In this section, the social desirability of R&D cooperation of leaders or followers in the early entrance setting is analyzed. Therefore, social welfare (SW), defined as the sum of consumer surplus[33] (CS) and producer surplus (PS) [34], is ranked across the five games, for both spillover symmetry and spillover asymmetry. These rankings are limited to some polar cases. More specifically, with symmetric spillovers, two scenarios are analyzed, i.e. no information sharing (β=0) and full information sharing

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[33] $CS = \frac{\left(\sum_{i=1}^{k} q_i^L + \sum_{j:k+1}^{n} q_j^F \right)^2}{2}$

[34] $PS = \sum_{i=1}^{k} \pi_i^L + \sum_{j:k+1}^{n} \pi_j^F$

(β=1). For asymmetric spillovers, it is assumed that there is no information sharing between leaders and between followers (β_{LL}=0 and β_{FF}=0), except for the case in which leaders or followers form an RJV cartel. In the description of the main tendencies, the focus of the analysis is restricted to only welfare.

Firstly, tendencies of welfare and consumer surplus are, just like in the simultaneous two stage models, (nearly always) the same, by which describing the tendencies of only welfare suffices. Moreover, it may not be that interesting to dwell upon the ranking of producer surplus. After all, leaders and followers are only concerned about their own profits and not about total producer surplus. Consequently, producer surplus will not always be maximized by firms. For example, when there is no information sharing with symmetric spillovers (β=0), producer surplus is the highest when leaders cooperate in an R&D cartel, but leaders' private incentives are to cooperate in an RJV cartel. It is important to notice that side payments, which are not allowed for in the model here, could change this line of reasoning. After all, when side payments would be feasible, leading firms could opt for the R&D cartel when this would result in the highest producer surplus. In that case, the side payments from the followers to the leaders should compensate the latter sufficiently for their lower profits in an R&D cartel compared to an RJV cartel. However, this discussion is beyond the scope of this study. A further reason to limit the analysis to welfare is that the main ambition of this section is to analyze the desirability of R&D cooperation from the society's point of view and not from the viewpoint of individual firms when we aim to derive policy implications.

Note furthermore that the impact of R&D cooperation on welfare depends on the same critical spillovers as the ones driving the impact of R&D cooperation on the R&D investments, see Proposition 2.7 and 2.8. For example, R&D cartelization among leaders results in higher welfare if and only if $\beta > \beta^{LC}$ for symmetric spillovers or $\beta_{LL} > \beta_{LL}^{C}$ for asymmetric spillovers. Note that with RJV cartelization among leaders, the spillover always exceeds its critical value, by which welfare is thus always higher with RJV cartelization than with R&D competition. Analogous tendencies apply to the impact of R&D cooperation among followers on welfare.

2.7.1. Symmetric spillovers

Two spillover scenarios are considered here, namely no information sharing (β=0) and full information sharing (β=1)[35]. The complete ranking is provided in Table 2.5. Proposition 2.10 summarizes the main tendencies. With symmetric spillovers, the number of leaders is important to determine which game yields the highest welfare.

Proposition 2.10. In the early entrance setting with symmetric spillovers, the number of leaders determines which game yields the highest welfare.

- When the number of leaders is small, society is best off when followers cooperate in an RJV cartel.
- When there is an intermediate to high number of leaders, society is best off when leaders cooperate in an RJV cartel.

From Proposition 2.10, it is clear that, for symmetric spillovers, society is always better off when leaders or followers form an RJV cartel. Moreover, whether it should be the leaders or the followers who should cooperate in R&D hinges critically on the market structure, i.e. the number of leaders and followers. When there are only a few leaders, welfare is highest when followers cooperate in an RJV cartel. But, on the contrary, in case there are a lot of leaders, it is better to let the first movers form an RJV cartel. Thus, in short, governments should motivate the larger groups of players to cooperate in R&D.

These tendencies originate from the impact of RJV cartelization on the level of R&D investments. Remember from section 2.5.1 that RJV cartelization among leaders (followers) always results in larger innovative efforts of leaders (followers) compared to R&D competition, by which output increases and the equilibrium price decreases, which is advantageous for consumers and society as a whole.

When the number of leaders is small, the increase in total R&D investments turns out to be higher with an RJV cartel among followers than with an RJV cartel among

[35] When spillovers are symmetric, it is obvious that with full information sharing, an R&D cartel among leaders (followers) and an RJV cartel among leaders (followers) yield the same CS, PS and SW.

leaders. For a large number of leaders, the opposite is true, thus there is a larger increase in total R&D investments with an RJV cartel among leaders.

It is again not appropriate to give too much weight to the benchmark case of symmetric spillovers. However, it is interesting to observe the possibility that consumers and society may be better off when followers cooperate in an RJV cartel in case there are only a few leaders. The question then is whether similar tendencies apply with asymmetries. In the next section, some findings on welfare implications with asymmetric spillovers are summarized.

2.7.2. Asymmetric spillovers

With asymmetric spillovers, the focus is again on some polar cases. More specifically, it is assumed that there are no within group spillovers. Only, by definition, with RJV cartelization, the spillover between the cooperating firms equals 1. Thus, β_{LL}=0 and β_{FF}=0 in games (N,N), (C,N) and (N,C); β_{LL}=1 and β_{FF}=0 in game (CJ,N); and β_{LL}=0 and β_{FF}=1 in game (N,CJ). In Table 2.6, it is summarized which game results in the highest CS, PS and SW.

The tendencies of welfare with asymmetric spillovers are more or less in line with the findings with symmetric spillovers, as can be observed in Proposition 2.11.

Proposition 2.11. In the early entrance setting with asymmetric spillovers, the number of leaders and the spillover from leaders to followers determine which game yields the highest welfare.

- With a small number of leaders, society is best off when followers cooperate in an RJV cartel.
- With an intermediate number of leaders, society is best off with an RJV cartel of leaders when there is idea diffusion from leaders to followers (β_{LF}=0) and with an RJV cartel of followers when there is blue print copying from leader to followers (β_{LF}=1).
- With a large number of leaders, society is best off when leaders cooperate in an RJV cartel.

Small *k*	β=0	$CS_{N,CJ}>CS_{CJ,N}>CS_{N,N}>CS_{N,C}>CS_{C,N}$	$PS_{C,N}>PS_{CJ,N}>PS_{N,C}>PS_{N,N}>PS_{N,CJ}$	$SW_{N,CJ}>SW_{CJ,N}>SW_{N,C}>SW_{N,N}>SW_{C,N}$
	β=1	$CS_{N,CJ}=CS_{N,C}>CS_{CJ,N}=CS_{C,N}>CS_{N,N}$	$PS_{N,CJ}=PS_{N,C}>PS_{CJ,N}=PS_{C,N}>PS_{N,N}$	$SW_{N,CJ}=SW_{N,C}>SW_{CJ,N}>SW_{C,N}>SW_{N,N}$
Intermediate or high *k*	β=0	$CS_{CJ,N}>CS_{N,CJ}>CS_{N,N}>CS_{N,C}>CS_{C,N}$	$PS_{C,N}>PS_{CJ,N}>PS_{N,C}>PS_{N,N}>PS_{N,CJ}$	$SW_{CJ,N}>SW_{N,CJ}>SW_{N,N}>SW_{N,C}>SW_{C,N}$
	β=1	$CS_{CJ,N}=CS_{C,N}>CS_{N,CJ}=CS_{N,C}>CS_{N,N}$	$PS_{CJ,N}=PS_{C,N}>PS_{N,CJ}=PS_{N,C}>PS_{N,N}$	$SW_{CJ,N}=SW_{C,N}>SW_{N,CJ}=SW_{N,C}>SW_{N,N}$

Table 2.5. Ranking of consumer surplus (CS), producer surplus (PS) and welfare (SW) in the early entrance setting with symmetric spillovers.

Small *k*	β_{LF}=0	$CS_{N,CJ}>CS_{CJ,N}>CS_{N,N}>CS_{N,C}>CS_{C,N}$	$PS_{C,N}>PS_{CJ,N}>PS_{N,C}>PS_{N,N}>PS_{N,CJ}$	$SW_{N,CJ}>SW_{CJ,N}>SW_{N,C}>SW_{N,N}>SW_{C,N}$
	β_{LF}=1	$CS_{N,CJ}>CS_{N,N}>CS_{N,C}>CS_{CJ,N}>CS_{C,N}$	$PS_{CJ,N}>PS_{N,C}>PS_{N,N}>PS_{C,N}>PS_{N,CJ}$	$SW_{N,CJ}>SW_{N,C}>SW_{N,N}>SW_{CJ,N}>SW_{C,N}$
Intermediate *k*	β_{LF}=0	$CS_{CJ,N}>CS_{N,CJ}>CS_{N,N}>CS_{N,C}>CS_{C,N}$	$PS_{C,N}>PS_{CJ,N}>PS_{N,C}>PS_{N,N}>PS_{N,CJ}$	$SW_{CJ,N}>SW_{N,CJ}>SW_{N,C}>SW_{N,N}>SW_{C,N}$
	β_{LF}=1	$CS_{N,CJ}>CS_{N,N}>CS_{N,C}>CS_{CJ,N}>CS_{C,N}$	$PS_{CJ,N}>PS_{C,N}>PS_{N,C}>PS_{N,N}>PS_{N,CJ}$	$SW_{N,CJ}>SW_{N,C}>SW_{N,N}>SW_{CJ,N}>SW_{C,N}$
High *k*	β_{LF}=0	$CS_{CJ,N}>CS_{N,CJ}>CS_{N,N}>CS_{N,C}>CS_{C,N}$	$PS_{C,N}>PS_{CJ,N}>PS_{N,C}>PS_{N,N}>PS_{N,CJ}$	$SW_{CJ,N}>SW_{N,CJ}>SW_{N,C}>SW_{N,N}>SW_{C,N}$
	β_{LF}=1	$CS_{CJ,N}>CS_{N,CJ}>CS_{N,N}>CS_{N,C}>CS_{C,N}$	$PS_{CJ,N}>PS_{C,N}>PS_{N,C}>PS_{N,N}>PS_{N,CJ}$	$SW_{CJ,N}>SW_{N,CJ}>SW_{N,C}>SW_{N,N}>SW_{C,N}$

Table 2.6. Ranking of consumer surplus (CS), producer surplus (PS) and welfare (SW) in the early entrance setting with asymmetric spillovers with β_{LL}=0 and β_{FF}=0 in games (N,N), (C,N) and (N,C.); β_{LL}=1 and β_{FF}=0 in game (CJ,N) and β_{LL}=0 and β_{FF}=1 in game (N,CJ).

The level of R&D investments lies again at the heart of these tendencies. With a small number of leaders, the increase in total R&D investments appears to be higher with an RJV cartel among followers than with an RJV cartel among leaders. For a large number of leaders, the opposite is true.

With an intermediate number of leaders, tendencies are a bit more complicated. When there is idea diffusion from leaders to followers (β_{LF}=0), the increase in total R&D investments is the highest when leaders form an RJV cartel, compared to game (N,N). But, when there is blue print copying to followers (β_{LF}=1), an RJV cartel among followers results in higher total R&D investments compared to an RJV cartel among leaders as the investments of the latter are reduced by to the free riding opportunities by the followers.

2.7.3. Policy implications

Although the analysis concerning the social desirability of R&D cooperation of leaders and followers has only focused on some polar spillover cases, the findings can be used to point to some implications for policy guidelines.

When there are only a few leaders, by which the industry is more or less concentrated, policy makers should encourage the following (smaller) firms to cooperate in R&D. Moreover, the R&D cooperating followers should also be motivated to increase their knowledge sharing, for example by cross-license agreements, meetings, exchanging R&D personnel etc.

Encouraging RJV cartelization of followers will also enhance technological leapfrogging. Indeed, from section 2.4.2, we know that RJV cartelization among second movers makes technological leapfrogging more likely. Note furthermore that followers benefit from forming an RJV cartel as they realize higher profits when they cooperate in R&D than when they compete in R&D.

Another advantage for policy makers, when encouraging only followers to cooperate, in R&D relates to the possible extension of R&D cooperation to collusion on the output market. After all, it is known that R&D cooperation makes it more likely that firms collude on the product market, thereby reducing welfare (Martin, 1995).

However, these welfare diminishing effects of collusion on the output market tend to be smaller when the R&D cooperating firms have less market power. From that perspective, it could thus be in the interest of governments to restrict R&D cooperation to only small firms (followers). However, it might sometimes be difficult for policy makers do distinguish between small and large firms. An indication of the market power of firms might be provided by their market shares (see also Motta, 2004).

2.8. Late entrance setting

A related but slightly different setting is the late entrance setting. This setting also consists of four stages, but their sequence differs from the early entrance setting, as has been detailed in section 2.2. After the investments of the market leaders in stage one, the leaders decide on their optimal output quantities in stage two. Market followers invest in R&D (stage three) after leaders' commitments to quantities. Finally, in stage four, the followers choose their output quantities. This setting is called, somewhat loosely, the late entrance setting.

Note that this setting could also represent the scenario in which innovative market leaders expect and encourage entry. A nice illustration stems from the copying machine industry in the 1960s. When Xerox was granted a patent on the electrofax copying process (an electrostatic copying technique using special coated paper), Xerox did not restrict entry. On the contrary, Xerox encouraged entry by licensing its technology to other (following) firms but Xerox has been able to benefit from moving first as Xerox controlled approximately 60% of the market at the end of the 1960s (Blackstone, 1968).

The aim of this section is to analyze whether the detected tendencies of the early entrance setting remain valid in the late entrance setting. Therefore, the same five games as in Table 2.1 are looked at. To indicate the difference in spillovers between the early and late entrance setting, the spillovers are here labelled by the symbol δ. Ex post unit costs and profit functions are given by equations (2.2), (2.3), (2.5) and (2.6) in which the symbol β needs to be replaced by δ. Figure 2.2 provides a graphical illustration of the late entrance setting and the different spillovers.

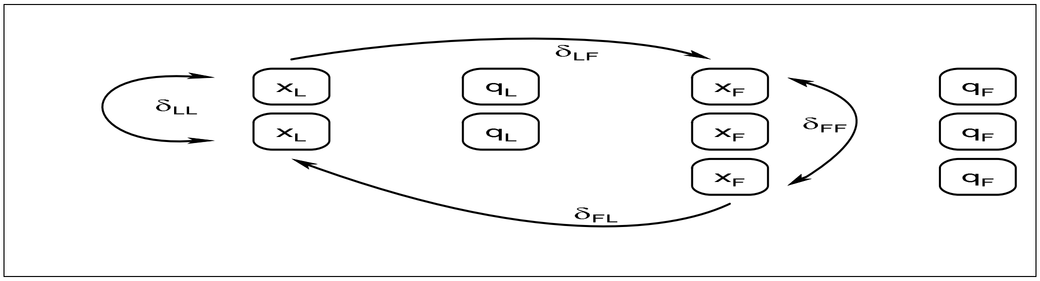

Figure 2.2. The late entrance setting for k=2 and n=5. Extension to the general case of $1 \leq k < n$ is obvious. The spillover from followers to leaders δ_{FL} is set equal to zero, except in the benchmark case of symmetric spillovers.

The same four groups of spillovers are considered. For completeness, Table 2.7 defines symmetric and asymmetric spillovers. As can be observed in Figure 2.2, spillovers from followers to leaders are again considered. However, the introduction of this spillover could be questioned, as the output stage of the leaders is ahead of the R&D investment stage of the followers. There are however two reasons to take the spillover from followers to leaders into account. Firstly, it is useful to do so as it is then easier to compare tendencies with the early entrance setting. Secondly, this assumption of a positive spillover from followers to leaders can be justified by assuming that the decisions on investment and output levels (of both leaders and followers) are credible commitments but that the actual conduct of the game takes place at once. Then, bi-directional spillovers between the group of leaders and the group of followers are possible.

	Symmetric Spillovers	Asymmetric Spillovers
(N,N), (C,N), and (N,C)	$\delta_{LL}=\delta_{LF}=\delta_{FF}=\delta_{FL}=\delta$	$\delta_{LL}\neq\delta_{LF}\neq\delta_{FF}$ and $\delta_{FL}=0$
(CJ,N)	$\delta_{LF}=\delta_{FF}=\delta_{FL}=\delta$ and $\delta_{LL}=1$	$\delta_{LF}\neq\delta_{FF}$, $\delta_{LL}=1$ and $\delta_{FL}=0$
(N,CJ)	$\delta_{LL}=\delta_{LF}=\delta_{FL}=\delta$ and $\delta_{FF}=1$	$\delta_{LL}\neq\delta_{LF}$, $\delta_{FF}=1$ and $\delta_{FL}=0$

Table 2.7. Definition of symmetric and asymmetric spillovers in the five games in the late entrance setting.

2.8.1. Impact of spillovers

In the late entrance setting, the impact of asymmetric spillovers on R&D investments of leaders and followers is exactly the same as in the early entrance setting. With spillover symmetry, however, some minor differences with the early entrance setting can occur but, in general, the impact of symmetric spillovers is similar.

Indeed, just like in the early entrance setting, R&D investments of leaders and followers are in general discouraged by an increase in the symmetric spillover. However, there are two exceptions. Firstly, R&D investments of R&D cartelized leaders are increasing when there are a lot of leaders (k>n/2), which was also the case in the early entrance setting. But now, moreover, followers' R&D investments always increase in the symmetric spillover when they form an R&D cartel. The latter tendency is different from the early entrance setting.

2.8.2. Impact of leading or following

Comparing strategic investments of leaders and followers in the late entrance setting yields more or less similar results as in the early entrance setting.

With symmetric spillovers, the comparison of leader and follower efforts is however slightly different and a bit more complicated than in the early entrance setting. The leaders, in general, invest more than the followers but larger efforts of the followers are also possible in a limited number of scenarios. First of all, just like in the early entrance setting, a few second movers tend to invest more then a large number of R&D cartelized first movers when the spillover is small (game (C,N)). Moreover, when both leaders and followers compete in R&D (game (N,N)), the followers invest more than the leaders when the number of leaders is high and the spillover is large. To continue, in games with competing leaders and R&D or RJV cartelized followers (games (N,C) and (N,CJ)), R&D investments of cooperating followers are higher than the investments of the leaders when the spillover is large. Finally, when leaders form an RJV cartel, In game (CJ,N), the leaders always invest more than the followers.

With asymmetric spillovers, it is assumed that there is no spillover from the followers to the leaders (δ_{FL}=0). The comparison of leader and follower R&D efforts is then again driven by the level of free riding opportunities of followers on leaders' innovative investments. In Tables 2.8a, 2.8b and 2.8c, some numerical examples of the equalizer spillover in the late entrance setting (δ_{LF}^{e}) are provided.

These simulations indicate that R&D competing followers tend to invest more than R&D competing leaders when there is blue print copying from leaders to followers and among leaders (δ_{LF}=δ_{LL}=1) and competing followers face a low internal spillover (game (N,N)).

Just like with early entrance, RJV cartelization among leaders might again be an appropriate tool for leaders to decrease the likelihood of technological leapfrogging by followers. For followers, RJV cartelization only turns out to be efficient in stimulating technological leapfrogging when there is a high spillover among the leaders. Thus again, R&D cooperation can be considered to be a tool for leaders and followers to discourage or stimulate technological leapfrogging.

n=10 k=2		δ_{FF} = 0	δ_{FF} = 1	n=10 k=5		δ_{FF} = 0	δ_{FF} = 1
δ_{LL}	0	δ_{LF}^e>1	δ_{LF}^e>1	δ_{LL}	0	δ_{LF}^e>1	δ_{LF}^e>1
δ_{LL}	1	δ_{LF}^e=0.792	δ_{LF}^e=1	δ_{LL}	1	δ_{LF}^e=0.215	δ_{LF}^e=0.999

Table 2.8a. Numerical examples (late entrance setting) for the equalizer spillover δ_{LF}^e in the game with R&D competition among leaders and R&D competition among followers (game (N,N)). Leaders invest more (less) than followers if and only if $\delta_{LF}<\delta_{LF}^e$ ($\delta_{LF}>\delta_{LF}^e$).

n=10 k=2		β_{FF} = 0	β_{FF} = 1	n=10 k=5		δ_{FF} = 0	δ_{FF} = 1
δ_{LL}	0	δ_{LF}^e =0.396	δ_{LF}^e =0.541	β_{LL}	0	δ_{LF}^e =0.040	δ_{LF}^e =0.200
δ_{LL}	1	δ_{LF}^e =0.958	δ_{LF}^e >1	β_{LL}	1	δ_{LF}^e =0.999	δ_{LF}^e >1

Table 2.8b. Numerical examples (late entrance setting) for the equalizer spillover δ_{LF}^e in the game with R&D cartelization among leaders and R&D competition among followers (game (C,N)). In the grey cells, the equalizer spillover values for the game with RJV cartelization among leaders and R&D competition among followers (game (CJ,N)) are indicated (δ_{LL}=1). Leaders invest more (less) than followers if and only if $\delta_{LF}<\delta_{LF}^e$ ($\delta_{LF}>\delta_{LF}^e$).

n=10 k=2		δ_{FF} = 0	δ_{FF} = 1	n=10 k=5		δ_{FF} = 0	δ_{FF} = 1
δ_{LL}	0	δ_{LF}^e >1	δ_{LF}^e >1	δ_{LL}	0	δ_{LF}^e >1	δ_{LF}^e >1
δ_{LL}	1	δ_{LF}^e >1	δ_{LF}^e >0.788	δ_{LL}	1	δ_{LF}^e =1	δ_{LF}^e =0.212

Table 2.8c. Numerical examples (late entrance setting) for the equalizer spillover δ_{LF}^e in the game with R&D competition among leaders and R&D cartelization among followers (game (N,C)). In the grey cells, the equalizer spillover values for the game with R&D competition among leaders and RJV cartelization among followers (game (N,CJ)) are indicated (δ_{FF}=1). Leaders invest more (less) than followers if and only if $\delta_{LF}<\delta_{LF}^e$ ($\delta_{LF}>\delta_{LF}^e$).

2.8.3. Impact of cooperation on R&D investments

With symmetric spillovers, tendencies are completely the same as in the early entrance setting. For the leaders, the critical spillover δ^{LC} equals $\frac{n-k+1}{n-k+2}$ while the critical spillover for the followers δ^{FC} is equal to ½.

When spillovers are asymmetric, R&D investments of both leaders and followers can be higher or lower when they form an R&D cartel. There is again a critical leader-specific spillover $\delta_{LL}{}^{C}$ determining the comparison of R&D investments of competing leaders versus leaders in an R&D cartel. However, the value of $\delta_{LL}{}^{C}$ differs slightly from the early entrance setting. Moreover, investments of the leaders in an RJV cartel always exceed the investments of R&D competing or R&D cartelized leaders[36]. R&D cartelization among followers yields higher R&D investments compared to R&D competition among followers if and only if the follower-specific spillover exceeds its critical value $\delta_{FF}{}^{C}$ with $\delta_{FF}{}^{C}$=½. Finally, followers always invest more in an RJV cartel than in an R&D cartel[37]. In Table 2.9, some values of the critical leader-specific spillover $\delta_{LL}{}^{C}$ are presented.

n=10 k=2		δ_{FF}		n=10 k=5		δ_{FF}	
		0	1			0	1
δ_{LF}	0	$\delta_{LL}{}^{C}$ =0.5	$\delta_{LL}{}^{C}$ =0.5	δ_{LF}	0	$\delta_{LL}{}^{C}$ =0.5	$\delta_{LL}{}^{C}$ =0.5
	1	$\delta_{LL}{}^{C}$ =0.945	$\delta_{LL}{}^{C}$ =0.945		1	$\delta_{LL}{}^{C}$ =0.917	$\delta_{LL}{}^{C}$ =0.917

Table 2.9. Numerical examples of the critical leader-specific spillover $\delta_{LL}{}^{C}$. R&D cooperation among leaders in an R&D cartel results in higher (lower) investments, compared to R&D competition, if and only if $\delta_{LL}>\delta_{LL}{}^{C}$ ($\delta_{LL}<\delta_{LL}{}^{C}$).

2.8.4. Impact of cooperation on profitability and welfare

The impact of cooperation on profitability yields the same tendencies compared to the early entrance setting. Leaders (followers) benefit from R&D cartelization, as their profits are always higher than with R&D competition. After all, R&D cooperation softens competition, by which profits are increased. Moreover, RJV cartelization is always most beneficial for leaders (followers).

[36] When δ_{LL}=1, R&D investments of cooperating leaders in an R&D cartel are the same as in an RJV cartel.

[37] When δ_{FF}=1, R&D investments of cooperating followers in an R&D cartel are the same as in an RJV cartel.

Tendencies of consumer surplus, producer surplus and welfare are very similar to the early entrance setting although some minor differences can be observed for producer surplus and welfare. In the appendix, the ranking of CS, PS and SW is detailed for both symmetric and asymmetric cases.

Again, the social desirability of R&D cooperation of leader or followers critically depends on the number of leaders. When the industry is dominated by only a few firms, society is best off with R&D cooperation of the followers. The same welfare tendencies as in the early entrance setting thus prevail here.

2.9. Conclusion

This study has shown the importance of accounting for the heterogeneity of firms in strategic investments games. After all, some firms are more innovative and take the role of leader while other firms pursue a more imitative strategy and take the role of follower. It is moreover typical that this heterogeneity results in asymmetric spillovers between leaders and followers. As R&D cooperation is a widely used policy instrument to enhance innovative activity, first or second movers have been allowed to bundle R&D forces. All in all, a four stage setting strategic investment setting with cost-reducing R&D has been considered. Both an early and a late entrance setting have been analyzed and similar results have been obtained.

Firstly, as for the impact of the spillovers on R&D investments of leaders and followers, it has been shown that tendencies can differ from the two stage models with simultaneous moves. More specifically, the symmetric spillover is usually exerting a negative impact on cooperative investments of leaders and followers, which is due to, respectively, the spillover from the leaders to the followers and the spillover from the followers to the leaders. However, with asymmetric spillovers, tendencies are the same as in the two stage models and are helpful in understanding tendencies with symmetric spillovers.

Secondly, the investments of leaders and followers have been compared for both symmetric and asymmetric spillovers. When spillovers are asymmetric, it has been pointed out that followers often devote more resources to R&D than leaders. This technological leapfrogging especially tends to take place when free riding opportunities for the followers are sufficiently large. Consequently, in order to discourage technological leapfrogging, leaders should try to minimize spillovers by for example limiting the movement of R&D employees to followers or by restricting knowledge transfers within the firm. However, it is obvious that followers, in their endeavour to catch up with leaders, will try to maximize the spillover from leaders to followers. Possible ways to do so are investments in absorptive capacity and the hunt for industry leaders' R&D personnel.

The findings of the study also indicate that R&D cooperation might be another instrument in the process of technological leapfrogging of which both leaders and followers can make use. On the one hand, bundling R&D forces in an RJV cartel can help leaders to avoid being leapfrogged by the followers. After all, RJV cartelized leaders invest more than R&D competing leaders by which followers need to increase their investments when they want to surpass the leaders. On the other hand, by forming an RJV cartel, followers can encourage technological leapfrogging. Note that the allowance for R&D cooperatives in the United States and in the European Community may be seen in this perspective. After all, a major objective of the permission for firms to cooperate in R&D in both regions was a response to their decline in technological lead over other regions, for example Japan (Hagedoorn et al., 2000).

To continue, the economic performance of R&D cooperation (R&D cartel or RJV cartel) has been compared with R&D competition. This analysis yields similar findings as in the two stage models with simultaneous moves. More specifically, critical spillovers drive this comparison, both with spillover symmetry and asymmetry. With symmetric spillovers, investments of leaders in an R&D cartel are higher than with R&D competition if the spillover is larger than $(n\text{-}k+1)/(n\text{-}k+2)$. Similarly, followers realize higher investments with R&D cooperation than with R&D competition if the symmetric spillover is larger than ½. When spillovers are asymmetric, critical leader-specific (follower-specific) spillovers again determine whether R&D cartelization enhances R&D investments compared with R&D competition. RJV cartelization always yields the highest investments. Note that the critical spillover for the leaders is sometimes rather high. In that case, only an RJV cartel might help the leaders to improve on their technology compared to R&D competition. However, as has been indicated, knowledge sharing may not always be perfect.

It has also been shown that R&D cartelization among leaders (followers) always results in an increase of profits compared to R&D competition. After all, R&D cartelization is a competition softening instrument, by which it is no wonder that leaders (followers) are better off when they form an R&D cartel.

Analyzing the effectiveness of R&D cooperation (in terms of consumer, producer and total surplus) is however a complicated task as the comparison across the different games in both the early and the late entrance setting strongly depends on the parameters of the model. Therefore, it is better to look at those scenarios in which the welfare is highest. On this basis, some basic insights can be obtained by which some policy guidelines could be formulated.

This analysis has demonstrated that appropriate government intervention strongly depends on the industry structure, i.e. the number of leaders and followers. More specifically, when there are a lot of leading firms, R&D cooperation among leaders should be stimulated. However, most industries are characterized by only a small number of dominating firms. In this case, governments should promote R&D cooperation among the small followers, as welfare is then highest. Governments could for example provide financial support for small firms in order to cope with the start-up costs of the venture. Note that by encouraging followers to cooperate, technological leapfrogging would be stimulated. Moreover, it is known that R&D cooperation often extends to collusion on the product market, thereby reducing welfare (Martin, 1995). Motta (2004) argues that these anti-competitive effects are less likely when small firms cooperate in R&D. A market share criterion could be used by governments to assess firms' market power.

Before moving to the next chapter, we would like to point to some limitations of the study here. Firstly, the spillover levels are assumed to be exogenous. In reality, it is known that firms try to minimize outgoing and maximize incoming spillovers (Cassiman et al., 2002). In addition, the study does not take into account the notion of absorptive capacity (Cohen and Levintahl, 1989), as this would unnecessary complicate the analysis. To continue, although the model allows for some asymmetries, spillovers are still assumed to be symmetric within each group. However, it could well be the case that spillovers within a group are asymmetric as well.

A second limitation concerns the exogenously determined roles of all the players. In this respect, it should be stressed that market leaders may not always move first in the innovation process. It would be interesting to endogenize the sequence of moves in the R&D stages, given the Stackelberg competition on the output market. Moreover, all firms, both leaders and followers, have the same ex ante unit costs and the same R&D cost function. It could be argued that leaders could have lower ex ante unit costs (due to past R&D experience) or could be more efficient in conducting R&D. However, by assuming ex ante symmetric firms, the analysis can focus more easily on the pure spillover effects.

To continue, in the study here, it has been assumed that all leaders or all followers cooperate in one R&D cooperative. However, it could of course be well the case that only some followers cooperate while others compete or form another R&D cooperative. Moreover, also cooperation between leaders and followers could be looked at.

Finally, a minor drawback of this study is the fact that results mainly rely on numerical simulations. However, it should be underlined that the expressions for optimal R&D investments are very complex, even for a small number of leaders and followers. Furthermore, in more and more studies, simulations are used to sketch the main tendencies in case analytical expressions get too complicated (see for example Atallah (2005)).

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Appendix

Ranking of consumer surplus, producer surplus and welfare in the late entrance setting

Late Entrance with symmetric spillovers

Small k	δ=0	$CS_{N,CJ}>CS_{CJ,N}>CS_{N,N}>CS_{N,C}>CS_{C,N}$	$PS_{C,N}>PS_{N,C}>PS_{CJ,N}>PS_{N,N}>PS_{N,CJ}$	$SW_{N,CJ}>SW_{CJ,N}>SW_{N,N}>SW_{N,C}>SW_{C,N}$
	δ=1	$CS_{N,CJ}=CS_{N,C}>CS_{CJ,N}=CS_{C,N}>CS_{N,N}$	$PS_{N,CJ}=PS_{N,C}>PS_{CJ,N}=PS_{C,N}>PS_{N,N}$	$SW_{N,CJ}=SW_{N,C}>SW_{CJ,N}=SW_{C,N}>SW_{N,N}$
Intermediate or high k	δ=0	$CS_{CJ,N}>CS_{N,CJ}>CS_{N,N}>CS_{N,C}>CS_{C,N}$	$PS_{C,N}>PS_{CJ,N}>PS_{N,C}>PS_{N,N}>PS_{N,CJ}$	$SW_{CJ,N}>SW_{N,CJ}>SW_{N,N}>SW_{N,C}>SW_{C,N}$
	δ=1	$CS_{CJ,N}=CS_{C,N}>CS_{N,CJ}=CS_{N,C}>CS_{N,N}$	$PS_{CJ,N}=PS_{C,N}>PS_{N,CJ}=PS_{N,C}>PS_{N,N}$	$SW_{CJ,N}=SW_{C,N}>SW_{N,CJ}=SW_{N,C}>SW_{N,N}$

Table 2.11. Ranking of consumer surplus (CS), producer surplus (PS) and welfare (SW) in the late entrance setting with symmetric spillovers.

Late Entrance with asymmetric spillovers

Small k	δ_{LF}=0	$CS_{N,CJ}>CS_{CJ,N}>CS_{N,N}>CS_{N,C}>CS_{C,N}$	$PS_{C,N}>PS_{N,C}>PS_{CJ,N}>PS_{N,N}>PS_{N,CJ}$	$SW_{N,CJ}>SW_{CJ,N}>SW_{N,N}>SW_{N,C}>SW_{C,N}$
	δ_{LF}=1	$CS_{N,CJ}>CS_{N,N}>CS_{N,C}>CS_{CJ,N}>CS_{C,N}$	$PS_{N,C}>PS_{CJ,N}>PS_{N,N}>PS_{C,N}>PS_{N,CJ}$	$SW_{N,CJ}>SW_{N,N}>SW_{N,C}>SW_{CJ,N}>SW_{C,N}$
Intermediate k	δ_{LF}=0	$CS_{CJ,N}>CS_{N,CJ}>CS_{N,N}>CS_{N,C}>CS_{C,N}$	$PS_{C,N}>PS_{CJ,N}>PS_{N,C}>PS_{N,N}>PS_{N,CJ}$	$SW_{CJ,N}>SW_{N,CJ}>SW_{N,N}>SW_{N,C}>SW_{C,N}$
	δ_{LF}=1	$CS_{N,CJ}>CS_{N,N}>CS_{N,C}>CS_{CJ,N}>CS_{C,N}$	$PS_{CJ,N}>PS_{N,C}>PS_{C,N}>PS_{N,N}>PS_{N,CJ}$	$SW_{N,CJ}>SW_{N,N}>SW_{N,C}>SW_{CJ,N}>SW_{C,N}$
High k	δ_{LF}=0	$CS_{CJ,N}>CS_{N,CJ}>CS_{N,N}>CS_{N,C}>CS_{C,N}$	$PS_{C,N}>PS_{CJ,N}>PS_{N,C}>PS_{N,N}>PS_{N,CJ}$	$SW_{CJ,N}>SW_{N,CJ}>SW_{N,N}>SW_{N,C}>SW_{C,N}$
	δ_{LF}=1	$CS_{CJ,N}>CS_{N,CJ}>CS_{N,N}>CS_{N,C}>CS_{C,N}$	$PS_{CJ,N}>PS_{C,N}>PS_{N,C}>PS_{N,N}>PS_{N,CJ}$	$SW_{CJ,N}>SW_{N,CJ}>SW_{N,N}>SW_{N,C}>SW_{C,N}$

Table 2.12. Ranking of consumer surplus (CS), producer surplus (PS) and welfare (SW) in the late entrance setting with asymmetric spillovers with δ_{LL}=0 and δ_{FF}=0 in games (N,N), (C,N) and (N,C.); δ_{LL}=1 and δ_{FF}=0 in game (CJ,N) and δ_{LL}=0 and δ_{FF}=1 in game (N,CJ).

3. Leadership persistence and technological leapfrogging in patent races without winner-takes-all

Joint Work with Professor Raymond De Bondt

This study focuses on the role of reward sharing in patent races with an incumbent and one or more entrants. It is shown that the comparison of the efforts of the incumbent and the entrants does not only depend on the assumptions regarding entry, i.e. exogenous versus endogenous entry, but also on how the rewards of the race are shared among the winner and the losers of the race. Indeed, when there is exogenous entry, it is possible that the incumbent invests more than the entrants, namely when a winning entrant shares with other (losing) entrants, thereby reversing the winner-takes-all finding of Reinganum (1985). Moreover, when there is endogenous entry, the incumbent may invest less than the entrants, when the winning incumbent needs to share but a winning entrant takes it all. Hence, also Etro's (2004) finding can be altered.

3.1. Introduction

It is well known that leading firms can sometimes dominate the market for a very long time period. Exemplifying are the longstanding dominant positions of Intel in the microprocessor industry, of the Renault Espace in the market for MPV's and of De Nul, Boskalis, Van Oord and DEME in the dredging industry (see 2.1). Other well-known examples are Microsoft in the industry of operating systems and Nokia in the market of mobile phones. To maintain their leadership positions, these firms intensively engage in research and development (R&D) activities in order to come up with new or improved products or technologies. For instance, in 2000, Microsoft's R&D expenditures equaled $3,7 billion (=16,4% of its total sales).

Indeed, actual or potential competitors do not rest on their laurels but also compete for the market. Moreover, it is not uncommon that one of these competitors manages to be the first to commercialize a new product and, subsequently, becomes the new market leader. For example, in the market for portable MP3 players, Creative used to be the market leader but was surpassed by Apple, because of its introduction of the

Ipod. The market for laser printers serves a second example. Although Hewlett-Packard is the market leader nowadays, the first laser printers were developed and commercialized by Xerox and IBM (Etro, 2007; McKenzie and Lee, 2006).

This kind of competition for the market is often modeled by stochastic patent races[38] in which there is one firm with the possibility of committing to a certain level of R&D investments before its competitors. After all, this firm can be seen as the market leader or an incumbent monopolist, due to for example a patent on a certain product or technology by which it is reasonable to assume that this firm moves first in the patent race. But actual competitors or potential entrants also invest in R&D. The first to successfully develop an innovation is the winner of the race and is granted a patent. These patent races can, in general, be classified along two dimensions, namely winner-takes-all versus market sharing and exogenous versus endogenous entry.

Firstly, patent races differ from each other in the way the rewards of the discovery are shared among the winner and the losers of the race. In race settings with winner-takes-all, it is assumed that the winner of the race gets the full value of the discovery. However, it could well be the case that the value of the innovation is shared among the winner and some or all losers. Then, the winner gets only a share of the total value of the innovation and the remainder of the 'cake' is divided among the losing firms. Indeed, losing firms can sometimes easily imitate an innovation. Mansfield et al. (1981), for example, find that on average 60% of patented innovations are imitated within a time period of 4 years.

The degree of reward sharing differs across industries as it depends heavily on the effectiveness of the patent. Other spillover mechanisms can enhance the imitation process, such as the ease of reverse engineering, mobility of personnel, meetings at professional conferences, publications, informal communication among engineers etc. In some industries, such as the semiconductors, computers and software, reward

[38] Reinganum (1989) distinguishes between symmetric and asymmetric patent races. In the symmetric models, all participants of the patent race decide simultaneously on their R&D investments (see for example Loury, 1979; Lee and Wilde, 1980; Reinganum, 1983 and Stewart, 1983). Asymmetric models are characterized by sequential moves. After all, in asymmetric patent races, there is an incumbent (e.g. a current patent holder) choosing its R&D investments before the entrants. These asymmetric models are therefore very suitable for the comparison of the R&D activity of a market incumbent with potential entrants (Reinganum, 1983; Reinganum, 1985).

sharing tends to be rather high as patents are usually offering weak protection to the innovator (Bessen and Maskin, 2000). But in other industries, a patent may yield strong protection. For example, Levin et al. (1987) argue that patent protection in the chemical industry tends to be rather effective as it may be rather easy to prove the uniqueness of a certain molecule[39].

A nice illustration of reward sharing is the story of the CAT scanners[40,41]. CAT scanners are instruments to take high quality three-dimensional pictures of internal organs of the body, based on the X-ray technology. As happens frequently, the invention of the CAT scanner was not the result of an active search for this technology but rather of luck. After all, while working as an engineer in the area of pattern identification and computer storage techniques at the Central Research Laboratories of the record company EMI in the late 1960s, Hounsfield hit upon a brilliant idea. By scanning the brain from multiple angles and reconstructing those images with computers, higher quality (compared to simple X-ray snapshots) and three-dimensional pictures of the human brain, would result. By late 1971, the first clinical tests of the brain scanner turned out to be promising and, although EMI lacked experience in the medical equipment industry, EMI decided to enter the scanner market, yielding the company a head start over its potential competitors. For a couple of years, EMI had the whole market for itself, but it was clear that other firms, which were active in other segments of the medical equipment industry, would enter this specific market. However, as brain scanners were already widely spread, entrants needed to come up with an improved technology as hospitals would of course not replace their current scanners with a similar one. So, the race for the full body scan took off. The entrants were indeed firms with more experience in the medical equipment industry, such as General Electric (GE), Pfizer, and Technicare but it was nevertheless EMI who won the race and was granted a patent for its full body scanner (mid 1970s). However, the company could enjoy its market leadership position for only a short period of time. After all, GE and Technicare entered the market with copycat products, thereby ignoring EMI's patents and EMI abandoned the market a

[39] Note that patent protection not only differs across industries but also across countries. For example, patent protection in the United States is stronger than in Japan, France, the United Kingdom and Germany (Martinez and Guellec, 2004).
[40] CAT is the acronym of Computed Axial Tomography.
[41] This example is based on Teece (1986), Trajtenberg (1990) and Schnaars (1994).

few years later[42]. So, although the market leader EMI won the race, it shared its prize to a large extent with the entrants in the CAT scanner market. This example points to the importance of analyzing reward sharing in patent races with sequential moves. However, until now, sharing of rewards has only been looked at in patent races with simultaneous moves (Stewart, 1983).

A second dimension of classification concerns exogenous (fixed) versus endogenous (free) entry. Until recently, the R&D behavior of the incumbent and the entrants has only been analyzed from a short run perspective, with a fixed number of firms, i.e. exogenous entry (Reinganum, 1985). Etro (2004), however, analyzes an asymmetric patent race with one incumbent and an endogenously determined number of entrants in a winner-takes-all setting. When there is free entry, firms keep on entering the industry until their (expected) profits equal zero. This free entry scenario corresponds to the long run. This distinction between exogenous and endogenous entry is however not without consequences when it comes to the comparison of the R&D investments of the incumbent and the entrants.

With exogenous entry and winner-takes-all, leapfrogging by an entrant is more likely than monopoly persistence as the incumbent invests less than each of the entrants by which an entrant is more likely to win the race (Reinganum, 1985). After all, when the number of entrants is given, the incumbent reduces its incentives as, due to the strategic complementarity between the investments of the incumbent and the entrants, the entrants also reduce their investments. Consequently, the probability of innovation shrinks, by which the lifespan of the incumbent's current patent increases, which is in the interest of the incumbent. However, the incentives to reduce efforts are lower for the entrants as they do not have to give up a current stream of profits when the innovation is obtained. This impact of the current patent on the incumbent's R&D incentives is in line with the replacement effect of Arrow (1962). As a result, potential entrants invest more in R&D than the incumbent. This tendency is consistent with empirical findings that, on average, challengers tend to invest more to enter a new market than incumbents (e.g. Czarnitzki and Kraft, 2004). With exogenous entry and

[42] It should be noted that also financial, marketing and distribution advantages helped the imitators to drive EMI out of the market.

winner-takes-all, Reinganum (1985) claims furthermore that the first mover has lower expected profits compared to the entrants (second mover advantages).

However, with endogenous entry and winner-takes-all, this finding is altered, so the incumbent invests more than each of the entrants. Etro (2004) shows that, with endogenous entry, the incumbent can neither influence the aggregate probability nor an entrant's individual probability of innovation. Thus, the incumbent can not extend the lifespan of the current patent by lowering its R&D investments. The only ambition of the incumbent is then to win the race and its incentives to do so are higher than those of the entrants. After all, the incumbent does not consider the impact of its investments on the aggregate probability of innovation, but entrants do take this impact into account as it reduces their expected profits and this explains why the incumbent invests more than the entrants. It may thus be clear that the assumption of free entry changes the incentives of the incumbent dramatically.

In this study, a closer look is taken at the behavior of incumbents and entrants in patent races, with exogenous or endogenous entry, when the rewards of a discovery are shared among the winner and the losers of the race. The purpose is to compare R&D investments of an incumbent monopolist and one or more entrants. By doing so, the study contributes to the extensive Schumpeterian debate on the impact of market power on R&D investment incentives. Moreover, by taking reward sharing into account, better insights are gained into the likelihood of leadership persistence or technological leapfrogging. Note that we especially do not use the term monopoly persistence here. After all, a winning incumbent monopolist is not necessarily the monopolist after the race, as there may be reward sharing with losing entrants. Furthermore, technological leapfrogging implies that one of the entrants is the first to innovate and is granted a patent on this new technology or product. Technological leapfrogging is also not necessarily resulting in a monopoly position for the winning entrant because of reward sharing.

Three different reward sharing scenarios are looked at. For each of these three scenarios, R&D investments and profits of incumbents and entrants are compared. The main finding is that sharing of rewards can change the comparison of the incumbent's and the entrants' efforts and profits, compared to winner-takes-all patent races. Firstly, with exogenous entry, the incumbent sometimes commits itself to higher investments than each of the entrants. Secondly, when entry is endogenous, situations are detailed in which entrants invest more than the incumbent. Thirdly, it is possible that the incumbent realizes higher expected profits than the entrants in a patent race with exogenous entry (first mover advantages).

In addition, by introducing reward sharing in patent races, the link with R&D behavior of firms in strategic investment games in the presence of spillovers can be made. More specifically, spillovers can be interpreted as an inverse measure of the strength of patent protection (Amir and Wooders, 1999). Then, a strong patent protection corresponds to a small spillover and vice versa. Analogously, spillovers and market sharing parameters can also be seen as measures of the pace of imitation. If a new product or a new technology is imitated shortly after its innovation, spillovers are large and there is a high degree of market sharing (cfr. blue print copying in chapter 2). On the other hand, when it takes a long time for second movers to imitate, spillovers are small and there is little sharing (cfr. idea diffusion in chapter 2). An interesting study combining spillovers and reward sharing is provided by Martin (2002) who models a patent race with both input and output spillovers. These output spillovers take place after the completion of the innovation and they define the sharing of the rewards. Hauenschild (2003) extends the output spillover model of d'Aspremont and Jacquemin (1988) and the input spillover model of Kamien et al. (1992) with R&D uncertainty in order to analyze and compare R&D performance in both models.

The remainder of this study goes as follows. In section 3.2, the patent race setting and the three reward sharing scenarios are described. Sections 3.3, 3.4 and 3.5 deal with the comparative statics of and the comparison between incumbent's and entrants' R&D investments in each of the three scenarios. Profits of the incumbent and the entrants are discussed in section 3.6. In section 3.7, R&D investments are compared with the socially optimal R&D investments and section 3.8 concludes.

3.2. The model

Stochastic innovative races with one first mover and several second movers are considered. The first mover is an incumbent monopolist, as it holds a patent on the current technology. Moreover, this patent results in a flow of current profits (π, with $\pi \geq 0$). The entrants are assumed not to be active in this specific market or industry at the beginning of the race and, hence, do not earn current profits[43]. For both the incumbent and the entrants, there is a fixed cost in order to participate in the patent race (*F*, with *F>0*). This fixed cost could for example be interpreted as the opportunity costs of entering this specific industry or market. Moreover, all firms continuously invest a flow of resources in R&D, z^L for the incumbent and z^i for the entrants (with $i=1,2,\ldots,n$). In other words, in each time unit, the incumbent and the entrants spend respectively z^L and z^i on R&D. Due to its leading position, the incumbent has the opportunity to commit to a certain R&D investment level before the entrants. When one of the racing firms has obtained the innovation, all firms immediately stop investing in R&D and a patent, with a private value *P*, is granted to the winner. One could think of *P* as representing the expected value of the profits obtained by the innovation.

The probability of discovering the new technology or new product at a certain point in time is assumed to be only dependent on the own and current R&D investments[44] and is given by the hazard rate function $h(.)$. Furthermore, it is assumed that $h(.)$ is concave and increasing, $h'(.)>0$ and $h''(.)<0$. Let $h\left(z^L\right)$ and $\sum_{i=1}^{n} h\left(z^i\right)$ be respectively the probability that the incumbent or one of the entrants is making the discovery at a certain point in time. Consequently, the probability that the incumbent discovers the innovation before time *t* is equal to $1-e^{-h\left(z^L\right)t}$. Analogously, the probability of success by one of the entrants before time t equals to $1-e^{\left(-\sum_{i=1}^{n} h\left(z^i\right)\right)t}$.

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[43] In the model here, the first mover is called the incumbent monopolist and the second movers are called entrants. Indeed, the latter are assumed not to be active in the incumbent's market before the race starts and do not enjoy current profits (in this market). Only the incumbent is active in this market and earns some profits. For example, only EMI was active in the market for CAT scanners and GE, Technicare and Pfizer were entrants in this specific market. However, the findings of this chapter may apply as well to scenarios in which one dominant firm and a number of smaller competitors compete for the market. For example, in the industry for operating systems, Microsoft is the market leader but some smaller players also try to conquer the market (e.g. Linux and Mac).

[44] This assumption reflects the memoryless nature of the patent race as the probability of winning the race depends neither on own past investments nor on the rival firms' past investments. For patent races with knowledge accumulation, see for example Doraszelski (2003).

Based on this information, the expected profit functions of the incumbent (3.1) and the entrants (3.2) can be formulated:

$$V^L = \int_{t=0}^{\infty} \left[\left(e^{-rt}\right) \left(e^{-h\left(z^L\right)t} \right) \left(e^{-\sum_{i=1}^{n} h\left(z^i\right)t} \right) \left(h\left(z^L\right) P_1^L + \sum_{i=1}^{n} h\left(z_i\right) P_2^L + \pi - z^L \right) \right] dt - F \tag{3.1}$$

$$V^i = \int_{t=0}^{\infty} \left[\left(e^{-rt}\right) \left(e^{-h\left(z^L\right)t} \right) \left(e^{-\sum_{i=1}^{n} h\left(z^i\right)t} \right) \left(h\left(z^i\right) P_1^i + h\left(z^L\right) P_2^i + \sum_{\substack{j=1 \\ j \neq i}}^{n} h\left(z^i\right) P_3^i - z^i \right) \right] dt - F \tag{3.2}$$

Integrating leads to the following expressions for the expected profits (as expected benefits *minus* expected R&D costs *minus* the fixed cost) of the incumbent (3.3) and the entrants (3.4):

$$V^L = \underbrace{\frac{h\left(z^L\right) P_1^L + \sum_{i=1}^{n} h\left(z_i\right) P_2^L + \pi}{r + \sum_{j=1}^{n} h\left(z^j\right) + h\left(z^L\right)}}_{\text{Expected Benefits}} - \underbrace{\frac{z^L}{r + \sum_{j=1}^{n} h\left(z^j\right) + h\left(z^L\right)}}_{\text{Expected R\&D Costs}} - \underbrace{F}_{\substack{\text{Fixed} \\ \text{Cost}}} \tag{3.3}$$

$$V^i = \underbrace{\frac{h\left(z^i\right) P_1^i + h\left(z^L\right) P_2^i + \sum_{\substack{j=1 \\ j \neq i}}^{n} h\left(z^i\right) P_3^i}{r + \sum_{j=1}^{n} h\left(z^j\right) + h\left(z^L\right)}}_{\text{Expected Benefits}} - \underbrace{\frac{z^i}{r + \sum_{j=1}^{n} h\left(z^j\right) + h\left(z^L\right)}}_{\text{Expected R\&D Costs}} - \underbrace{F}_{\substack{\text{Fixed} \\ \text{Cost}}} \tag{3.4}$$

with P_1^L the rewards for the incumbent if the incumbent wins,

P_2^L the rewards for the incumbent if an entrant wins,

P_1^i the rewards for entrant *i* if entrant i wins,

P_2^i the rewards for entrant *i* if the incumbent wins and

P_3^i the rewards for entrant *i* if another entrant wins.

The values of these payoffs depend on how the value of the innovation is shared among the winner and the losers of the race. The market sharing parameter is indicated by σ with $\sigma \leq 1$. A high value of σ corresponds to a small degree of reward sharing and a small value of σ refers to a large degree of reward sharing. Three different reward sharing scenarios are looked at. These three scenarios are summarized in table 3.1.

The first asymmetric reward sharing scenario (A1) is based on the story of EMI, described in the introduction of this chapter. As a winning incumbent in the market for CAT scanners, EMI lost (part of) the market to the losing entrants. In this scenario, it is further assumed that winning entrants take it all. For example, due to their experience in the medical equipment industry, it is not unreasonable to assume that GE or Technicare would have been able to better appropriate the returns from the innovation when one of them would have won the race.

In the second asymmetric scenario (A2), the winning incumbent takes it all, but a winning entrant shares with the other entrants. In the chemical industry for example, it is not uncommon that the leading firm uses a totally different technology compared to small firms[45]. Consequently, a breakthrough in a technology by the leader can not be used by any small following firm. Vice versa, when a small firm invents an improved production technology, the leader does not reap some of the fruits of that new technology but other small firms may copy some part of the new production process, as these small firms are less able to protect their knowledge and their production processes are similar. This second asymmetric reward sharing scenario may also represent industries in which entrants or small firms kind of cooperate in the patent race. After all, Freel and Harrison (2006) show that small or medium sized firms often cooperate with each other in order to develop a new product or a new process. Here, cooperation is defined as the commitment to share information and ideas about new products or production processes. An example of cooperation in the competition for the market may be the search of K-Mart for a partner in the competition for the North American Retail market, dominated by Wal-Mart (The Economist, 1998).

Besides these two asymmetric reward sharing scenarios, a closer look is also taken at symmetric reward sharing. For example, in the industry for mobile phones, innovations of leading firms are copied by small firms and vice versa. Indeed, the first mobile phone with internet connectivity was developed by Nokia, the leader in the industry. But also smaller mobile phone producers can be the first to introduce an innovative cell phone. SHARP, for example, was the first to commercialize a mobile

[45] See also footnote 43.

phone with a camera. However, nowadays, all mobile phones producers market models with internet connectivity and a camera.

Mathematically, the reward sharing scenarios go as follows. In the symmetric reward sharing scenario, the winner of the race gets σP and the remaining part of the discovery, $(1-\sigma)P$, is divided among the *n* losing firms, by which each loser of the race gets $\frac{(1-\sigma)}{n}P$. This reward sharing scenario is labeled as patent race S. Note that the symmetric reward sharing scenario is to some extent comparable with the symmetric spillover scenario in chapter 2.

In the first asymmetric reward sharing patent race, A1, a winning incumbent needs to share with all entrants by which the former gets σP and the rewards for each losing entrant equal $\left(\frac{1-\sigma}{n}\right)P$. If an entrant would win the race, he takes it all and the other firms get nothing. Again, the link with the model described in chapter 2 can be made. Here, this asymmetric situation is more or less similar to the situations in which there are high spillovers from leaders to followers.

Finally, in patent race A2, a winning entrant shares with the other entrants while the winning incumbent takes it all. Consequently, a winning entrant gets σP and each of the other (losing) entrants still realizes a payoff of $\left(\frac{1-\sigma}{n-1}\right)P$. The rewards for a winning incumbent equal the full value of the discovery *P*.

These three different reward sharing scenarios are analyzed with exogenous entry, in which the number of firms is given, and with free entry, in which the number of firms is determined endogenously. When entry is exogenous, the discussion only focuses on parameter values of *P*, *V*, *n*, σ, π and *r* for which $V^L(z^L,z)>0$ and $V(z^L,z)>0$ (positive profit condition). With endogenous entry, only parameter values of *P*, *V*, σ, π and *r* are allowed for which $V^L(z^L,z,n^*)>0$ (positive profit condition) and $V^i(z^L,z,n^*)=0$ (zero profit condition), with n^* the equilibrium number of firms.

One incumbent and n entrants		Scenario S Symmetric Sharing	Scenario A1 A winning entrant takes it all	Scenario A2 Winning incumbent takes it all
Rewards for the incumbent	P_1^L (incumbent wins)	σP	σP	P
	P_2^L (entrant wins)	$\left(\frac{1-\sigma}{n}\right)P$	0	0
Rewards for entrant i	P_1^i (entrant wins)	σP	P	σP
	P_2^i (incumbent wins)	$\left(\frac{1-\sigma}{n}\right)P$	$\left(\frac{1-\sigma}{n}\right)P$	0
	P_3^i (other entrant wins)	$\left(\frac{1-\sigma}{n}\right)P$	0	$\left(\frac{1-\sigma}{n-1}\right)P$

Table 3.1. Rewards for the incumbent and the entrants in the three different reward sharing scenarios.

3.3. Symmetric reward sharing

In this section, tendencies of the symmetric reward sharing patent races are described. For both the exogenous and the endogenous patent race, the R&D investments of the incumbent and the potential entrants are compared, after some comparative statics have been dealt with. Firstly, however, the game is solved in a general way. Specific characteristics of exogenous or endogenous entry are detailed afterwards.

3.3.1. Solutions

When there is symmetric reward sharing, the expected profits of the incumbent and the entrants are given by, respectively, equations (3.5) and (3.6) (see (3.3) and (3.4) and Table 3.1):

$$V^L = \frac{h\left(z^L\right)\sigma P + \sum_{j=1}^{n} h\left(z^j\right)\left(\frac{1-\sigma}{n}\right)P + \pi - z^L}{r + \sum_{j=1}^{n} h\left(z^j\right) + h\left(z^L\right)} - F \tag{3.5}$$

$$V^i = \frac{h\left(z^i\right)\sigma P + h\left(z^L\right)\left(\frac{1-\sigma}{n}\right)P + \sum_{\substack{j=1\\ j\neq i}}^{n} h\left(z^j\right)\left(\frac{1-\sigma}{n}\right)P - z^i}{r + \sum_{j=1}^{n} h\left(z^j\right) + h\left(z^L\right)} - F \,. \tag{3.6}$$

The two stage game is solved by backward induction. Each of the entrants maximizes its expected profits by choosing independently its level of R&D investments z^i, after having observed the investments of the incumbent:

$$\frac{\partial V^i}{\partial z^i} = \left. \begin{array}{l} \left[h'\left(z^i\right)\sigma P - 1\right]\left[r + \sum_{j=1}^{n} h\left(z^j\right) + h\left(z^L\right)\right] \\ -\left[h'\left(z^i\right)\right]\left[h\left(z^i\right)\sigma P + h\left(z^L\right)\left(\frac{1-\sigma}{n}\right)P + \sum_{\substack{j=1\\ j\neq i}}^{n} h\left(z^j\right)\left(\frac{1-\sigma}{n}\right)P - z^i\right] \end{array} \right/ \left[r + \sum_{j=1}^{n} h\left(z^j\right) + h\left(z^L\right)\right]^2 = 0 \tag{3.7}$$

In a symmetric equilibrium, the R&D investments of all entrants are the same ($z^i = z$, for i=1,...,n), yielding the following expression:

$$\phi^i = \left[h'(z)\sigma P - 1\right]\left[r + nh(z) + h\left(z^L\right)\right] - \left[h'(z)\right]\left[h(z)\left(1 - \frac{1-\sigma}{n}\right)P + h\left(z^L\right)\left(\frac{1-\sigma}{n}\right)P - z\right] = 0 \tag{3.8}$$

Maximizing the profits of the incumbent results in:

$$\frac{\partial V^L}{\partial z^L} = \left. \begin{array}{l} \left[h'\left(z^L\right)\sigma P + \frac{\partial\left(nh(z)\right)}{\partial z^L}\left(\frac{1-\sigma}{n}\right)P - nh(z)\frac{\partial n}{\partial z^L}\left(\frac{1-\sigma}{n^2}\right)P - 1\right]\left[r + nh(z) + h\left(z^L\right)\right] \\ -\left[h'\left(z^L\right) + \frac{\partial\left(nh(z)\right)}{\partial z^L}\right]\left[h\left(z^L\right)\sigma P + h(z)(1-\sigma)P + \pi - z^L\right] \end{array} \right/ \left[r + nh(z) + h\left(z^L\right)\right]^2 = 0 \tag{3.9}$$

Or equivalently,

$$\phi^L = \begin{array}{l} \left[h'\left(z^L\right)\sigma P + \frac{\partial\left(nh(z)\right)}{\partial z^L}\left(\frac{1-\sigma}{n}\right)P - nh(z)\frac{\partial n}{\partial z^L}\left(\frac{1-\sigma}{n^2}\right)P - 1\right]\left[r + nh(z) + h\left(z^L\right)\right] \\ -\left[h'\left(z^L\right) + \frac{\partial\left(nh(z)\right)}{\partial z^L}\right]\left[h\left(z^L\right)\sigma P + h(z)(1-\sigma)P + \pi - z^L\right] \end{array} = 0 \tag{3.10}$$

Now, define the following function[46,47]:

$$g_S(x) = \begin{array}{l} \left[h'(x)\sigma P + \frac{\partial\left(nh(z)\right)}{\partial z^L}\left(\frac{1-\sigma}{n}\right)P - nh(x)\frac{\partial n}{\partial z^L}\left(\frac{1-\sigma}{n^2}\right)P - 1\right]\left[r + nh(z) + h\left(z^L\right)\right] \\ -\left[\psi_S\right]\left[h(x)\sigma P + h(x)(1-\sigma)P + \pi - x\right] \end{array} \tag{3.11}$$

with $g_S\left(z^L\right) = 0$,

$g'_S(x) = \left.\frac{\partial \phi^L}{\partial z^L}\right|_{z^L = x} - h'(x)\left[h'(x)\sigma P + \frac{\partial\left(nh(z)\right)}{\partial z^L}\left(\frac{1-\sigma}{n}\right)P - nh(z)\frac{\partial n}{\partial z^L}\left(\frac{1-\sigma}{n^2}\right)P - 1\right]$ and

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46 The subscript S refers to the symmetric reward sharing scenario.

47 With exogenous entry: $\frac{\partial n}{\partial z^L} = 0$.

$$\psi_S = h'(x) + \left.\frac{\partial\left(nh(z)\right)}{\partial z^L}\right|_{z^L=x}.$$

Combining (3.8) and (3.11) and evaluating in x=z yields:

$$g_S(z) = \begin{array}{l} h'(z)\left[h\left(z^L\right)\left(\frac{1-\sigma}{n}\right)P - h(z)\left(\frac{1-\sigma}{n}\right)P\right] - h'(z)\pi \\ +\frac{\partial\left(n\times h(z)\right)}{\partial z^L}\left[\left(\frac{1-\sigma}{n}\right)P\left(r+nh(z)+h\left(z^L\right)\right)-\left(h(z)\sigma P+\pi-z\right)\right] \\ -nh(x)\frac{\partial n}{\partial z^L}\left(\frac{1-\sigma}{n^2}\right)P\left(r+nh(z)+h\left(z^L\right)\right)\end{array} \quad (3.12)$$

The comparison of the R&D investments of the incumbent and the entrants is driven by the sign of $g_S(z)$. If the sign of $g_S(z)$ is positive, the incumbent invests more than each entrant. A negative sign of $g_S(z)$ indicates higher R&D investments of each entrant. At this point, a distinction between exogenous and endogenous entry needs to be made.

3.3.2. Exogenous entry

3.3.2.1. Comparative statics

The comparative statics of the investments of the incumbent and the entrants are obtained by numerical simulations[48]. The following table summarizes the impact of the different parameters on the R&D investments of the incumbent and the entrants.

$\frac{\partial x^L}{\partial \sigma} > 0$	$\frac{\partial x^L}{\partial n} > 0$	$\frac{\partial x^L}{\partial P} > 0$	$\frac{\partial x^L}{\partial F} = 0$	$\frac{\partial x^L}{\partial \pi} < 0$	$\frac{\partial x^L}{\partial r} > 0$
$\frac{\partial x}{\partial \sigma} > 0$	$\frac{\partial x}{\partial n} > 0$	$\frac{\partial x}{\partial P} > 0$	$\frac{\partial x}{\partial F} = 0$	$\frac{\partial x}{\partial \pi} < 0$	$\frac{\partial x}{\partial r} > 0$

Table 3.2. Comparative statics in the symmetric reward sharing patent race with exogenous entry.

The investments of both the incumbent and the entrants are an increasing function of the market sharing parameter σ. Thus, the larger the part for the winner of the race is, the more the firms are willing to invest in order to increase the probability of winning the race. This tendency is analogous to the negative impact of symmetric spillovers on competitive R&D investments in strategic investment games with a given number of firms (see for example section 2.3.1).

[48] All numerical simulations in this chapter are obtained by using Maple.

Moreover, the number of entrants has a positive effect on the level of R&D investments of both the incumbent and the entrants. To continue, it is clear that a higher value of the discovery *P* provokes higher investments of all racing firms. When the discovery would be a gold mine, for example, the gold diggers will search more intensively when the expected value of the mine is higher. The interest rate *r* has also a positive impact on the R&D investments while there is no influence of the fixed cost *F*. The negative effect of the incumbent's current profits on its investments reflects Arrow's replacement effect. The investments of the entrants are also decreasing in the current profits.

3.3.2.2. Comparison of R&D investments of the incumbent and the entrants

With market sharing (σ<1), the sign of $g_S(z)$ is unclear[49] as the first term of (3.12) depends on the sign of $\left[h\left(z^L\right)-h(z)\right]$, which is of course unknown. Therefore, the comparison of the incumbent's and the entrants' efforts needs to rely on numerical simulations. These simulations indicate that an entrant always invests more than the incumbent. Consequently, the finding of Reinganum can be generalized to patent races with exogenous entry and symmetric reward sharing. This tendency is formalized in Proposition 3.1.

Proposition 3.1. In a patent race with symmetric market sharing and exogenous entry, each entrant always invests more than the incumbent, for all possible values of the market sharing parameter σ.

The intuition behind this result is an extension of the winner-takes-all setting with exogenous entry (Reinganum, 1985). Indeed, the incumbent tries to expand the lifespan of the current patent by lowering its R&D investments as then, due to the strategic complementarity between the investments of the incumbent and the entrants[50], the entrants also reduce their investments. But now, market sharing further discourages the incumbent and the entrants to invest in R&D. However, the incentives

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[49] When σ=1, the game is reduced to the winner-takes-all scenario, so the incumbent invests less than each entrant (Reinganum, 1985). Indeed, $g_S(z)\big|_{\sigma=1} = -\frac{\partial(nh(z))}{\partial z^L}\left[\left(h(z)P+\pi-z\right)\right]-h'(z)\pi<0$.

[50] Indeed, simulations indicate indeed that $\frac{\partial z}{\partial z^L}>0$ for all possible values of σ.

to cut down investments are lower for the entrants than for the incumbent as only the incumbent enjoys a current stream of profits by which each entrant invests more in R&D than the incumbent. Consequently, the entrant has a higher probability of winning the race and it is thus more likely that the entrant will show up with the innovation. Technological leapfrogging is thus more likely than leadership persistence.

Figure 3.1 provides some graphical illustrations of the investments of the incumbent and an entrant in function of the sharing parameter σ, for different values of n.

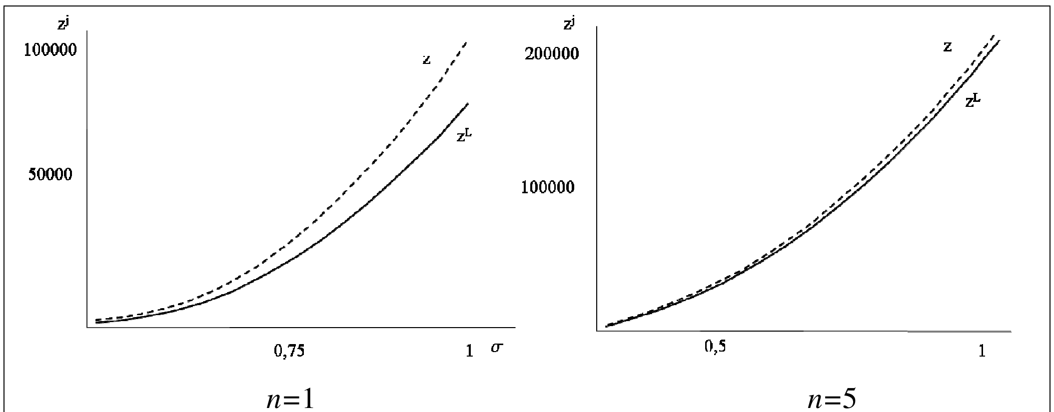

Figure 3.1. Symmetric reward sharing with exogenous entry. R&D investments of the incumbent and an entrant in function of σ, with P=1000, F=10, r=0.10, π=0, $h(x)=\sqrt{x}$, n=1 and n=5. The full line represents the investments of the incumbent (z^L) and the dashed line represents the investments of an entrant (z).

3.3.3. Endogenous entry

In a long run symmetric equilibrium, the zero profit condition states that the expected profits of the entrants are equal to zero:

$$ZPC_S=\left[\left(1-\frac{1-\sigma}{n}\right)h(z)P+h\left(z^L\right)\left(\frac{1-\sigma}{n}\right)P-z\right]-F\left[r+nh(z)+h\left(z^L\right)\right]=0 \tag{3.13}$$

Equation (3.13) determines the equilibrium number of entrants n^*. This equilibrium number of entrants is negatively related to the investments of the incumbents. In other words, by enhancing its investments, the incumbent can reduce the number of entrants. In addition, combining (3.8) with (3.13) yields:

$$h'(z)(\sigma P - F) = 1 \tag{3.14}$$

From (3.14), the R&D investments of the entrants z can be calculated and (3.14) clearly indicates that z does not depend on z^L. Moreover, z is also independent of r and π.

From ZPC$_S$, $\left.\frac{\partial(nh(z))}{\partial z^L}\right|_{zL=x}$ and $\left.\frac{\partial n}{\partial z^L}\right|_{zL=x}$ can be calculated (see appendix):

$$\left.\frac{\partial(nh(z))}{\partial z^L}\right|_{z^L=x} = \left.\frac{\partial n}{\partial z^L}h(z)\right|_{z^L=x} \tag{3.15}$$

with $\left.\frac{\partial n}{\partial z^L}\right|_{z^L=x} = \frac{h'(x)\left[\left(\frac{1-\sigma}{n}\right)P - F\right]}{h(x)\left(\frac{1-\sigma}{n^2}\right)P - h(z)\left(\frac{1-\sigma}{n^2}\right)P + Fh(z)}$

Substituting (3.15), for x=z, in (3.12) yields:

$$g_S(z) = \frac{h'(z)\left[h(z^L)\left(\frac{1-\sigma}{n}\right)P - h(z)\left(\frac{1-\sigma}{n}\right)P\right] - h'(z)\pi}{-\left[\frac{h'(z^L)\left[\left(\frac{1-\sigma}{n}\right)P - F\right]}{\left(\frac{1-\sigma}{n^2}\right)\frac{h(z^L)}{h(z)} - \left(\frac{1-\sigma}{n^2}\right)P + F}\right]\left[h(z) + \pi - z\right]} \tag{3.16}$$

3.3.3.1. Comparative statics

In patent races with symmetric reward sharing and free entry (see Table 3.3), the investments of the incumbent and the entrants are an increasing function of the sharing parameter σ and the value of the discovery P. The interest rate r has no effect on the R&D investments of the incumbent and the entrants. When considering the impact of the fixed cost F and the current profits π, a distinction needs to be made between the winner-takes-all (σ=1) and the reward sharing scenario (σ<1). In the former, as has been discussed by Etro (2004), the incumbent's investments are independent of F and π while in the latter they are decreasing in F and π. The investments of the entrants are negatively affected by the fixed cost F while there is no impact of π on efforts of the entrants.

The equilibrium number of entrants n^* is decreasing in σ by which the number of entrants is the lowest when there is winner-takes-all. The current profits of the incumbent have no impact on the equilibrium number of firms when there is winner-takes-all as both the incumbent's and the entrants' efforts are then unaffected by a change in π. However, when there is reward sharing, the equilibrium number of entrants is increasing in the current profits. Indeed, with reward sharing, an increase of the current profits reduces the incumbent's investments and, hence, more entrants enter the race. The value of the discovery P has a positive effect on n^* while there is no impact of r and a negative impact of the fixed cost F.

$\frac{\partial x^L}{\partial \sigma} > 0$	$\frac{\partial x^L}{\partial P} > 0$	$\frac{\partial x^L}{\partial F} = 0$ with $\sigma=1$ $\frac{\partial x^L}{\partial F} < 0$ with $\sigma<1$	$\frac{\partial x^L}{\partial \pi} = 0$ with $\sigma=1$ $\frac{\partial x^L}{\partial \pi} < 0$ with $\sigma<1$	$\frac{\partial x^L}{\partial r} = 0$
$\frac{\partial x}{\partial \sigma} > 0$	$\frac{\partial x}{\partial P} > 0$	$\frac{\partial x}{\partial F} < 0$	$\frac{\partial x}{\partial \pi} = 0$	$\frac{\partial x}{\partial r} = 0$
$\frac{\partial n^*}{\partial \sigma} < 0$	$\frac{\partial n^*}{\partial P} > 0$	$\frac{\partial n^*}{\partial F} < 0$	$\frac{\partial n^*}{\partial \pi} = 0$ with $\sigma=1$ $\frac{\partial n^*}{\partial \pi} > 0$ with $\sigma<1$	$\frac{\partial n^*}{\partial r} = 0$

Table 3.3. Comparative statics in the symmetric reward sharing patent race with endogenous entry.

Current profits and the incumbent's R&D investments

The negative effect of current profits on the incumbent's investments with reward sharing deserves some further attention as this is an important difference with the winner-takes-all scenario. Therefore, the impact of the current profits π is detailed for both σ=1 and σ<1.

When there is a winner-takes-all scenario (σ=1), the zero profit condition (3.13) can be rewritten as follows:

$$h(z)P - z = F\left[r + nh(z) + h\left(z^L\right)\right] \tag{3.17}$$

From this expression, it is clear that, by reducing its investments, the incumbent is not able to expand the lifespan of the current patent. Indeed, the investments of the entrants are independent of the investments of the incumbent (see 3.14). Consequently the left hand side of (3.17) remains unchanged when the incumbent lowers its investments. It is then obvious that the right hand side of (3.17) also needs to stay as it is. In other words, the aggregate probability of innovation can not be reduced by the incumbent, by which it is impossible to affect the lifespan of the current patent. Thus, the current stream of profits π does not play a role for the incumbent when deciding on its R&D investments when there is winner-takes-all (Etro, 2004).

However, when there is some market sharing (σ<1), the intuition changes. Consider again the zero profit condition (3.13), which is now rewritten as:

$$\left(1-\frac{1-\sigma}{n}\right)h(z)P+h\left(z^{L}\right)\left(\frac{1-\sigma}{n}\right)P-z=F\left[r+nh(z)+h\left(z^{L}\right)\right]. \tag{3.18}$$

Now, when the incumbent cuts down its R&D investments, it is at first sight not clear what happens with the aggregate probability of innovation. After all, lower R&D investments of the incumbent result in a higher number of entrants. Numerical simulations indicate that a reduction in z^L and its concomitant increase in n negatively affect the (left and) right hand side of (3.18). Thus, by reducing its R&D investments, the incumbent can lower the aggregate probability of innovation and hence increase the lifespan of the current patent. The higher the value of this current patent in terms of profits is, the higher the incumbent's incentives are to lower its R&D investments.

3.3.3.2. Comparison the R&D investments of the incumbent and the entrants

In the winner-takes-all scenario with free entry, the incumbent invests more than each entrant[51] (Etro, 2004). When there is symmetric sharing of rewards, σ<1, and π=0, the sign of $g_S(z)$ is unclear as it depends on the sign of $\left[h\left(z^{L}\right)-h(z)\right]$. Numerical simulations, however, indicate that Etro's tendency can be generalized to patent races with endogenous entry and symmetric reward sharing. However, when the current profits π are sufficiently large and there is reward sharing, it is possible that the entrants invest more than the incumbent. Proposition 3.2 formalizes and Figure 3.2 illustrates.

[51] For σ=1, $g_A(z)\big|_{\sigma=1}=h'(z)\times\left[h(z)\times P-z\right]>0$.

Proposition 3.2. In a patent race with symmetric market sharing and endogenous entry, the incumbent always invests more than an entrant, for all possible values for the reward sharing parameter σ and π=0. When σ<1, this tendency can be reversed when the current profits π are sufficiently large.

Consider first the case in which there are no current profits (π=0). When there is winner-takes-all, it has been shown that the incumbent can not influence the aggregate probability of innovation. Moreover, as investments of entrants are independent of the efforts of the incumbent, the incumbent can also not change the individual probability of innovation by an entrant. Consequently, the only remaining ambition of the incumbent is then to win the race. In its raid to win the race, the incumbent does not take the impact on the aggregate probability of innovation into account. However, this impact is taken into account by the entrants and reduces their incentives. Hence, the incumbent invests more than the entrants.

Reward sharing reduces investment incentives of both the incumbent and the entrants compared to the winner-takes-all scenario. Moreover, the ambition of the incumbent to win the race is now countered by an incentive to expand the lifespan of the current patent. After all, from (3.14), we know that the incumbent can not influence the individual probability of innovation of an entrant. Consequently, in order to be more likely to win the race, the incumbent should invest more than the entrant. However, with reward sharing, the incumbent can extend the lifespan of the current patent by reducing its R&D investments. These incentives to lower its investments are higher the larger the current profits are. Now, with small current profits, it turns out that the incentive to win the race offsets the incentive to extend the lifespan of the current patent. In this case, the incumbent invests most and thus leadership persistence is most likely. Only when the current profits are very large, the incentive of extending the lifespan of the current patent becomes more important than the incentive to win the race.

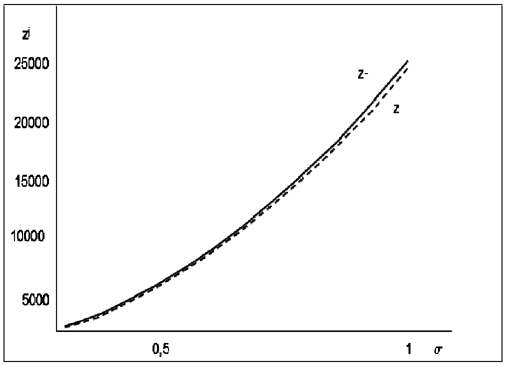

Figure 3.2. Symmetric reward sharing with endogenous entry. R&D investments of the incumbent and an entrant in function of σ, with P=1000, F=10, r=0.10, π=0, $h(x)=\sqrt{x}$. The full line represents the investments of the incumbent (z^L) and the dashed line represents the investments of an entrant (z).

3.4. Asymmetric reward sharing A1: winning follower takes it all

In this section, the first asymmetric scenario, labeled A1, is dealt with. As has been detailed in section 3.2 and in Table 3.1, a winning incumbent (for example EMI) shares with the losing entrants, while a winning entrant takes it all. For both the exogenous and endogenous entry scenario, the investments of the incumbent and the entrants are compared and some comparative statics are provided. The analysis starts with the general solution of this specific type of asymmetric reward sharing patent races.

3.4.1. Solutions

Combining the specific characteristics concerning the sharing of the rewards, as detailed in Table 3.1, with equations (3.3) and (3.4) allows formulating the expected profit functions of the incumbent (3.19) and the entrants (3.20):

$$V^L = \frac{h\left(z^L\right)\sigma P + \pi - z^L}{r + \sum_{j=1}^{n} h\left(z^j\right) + h\left(z^L\right)} - F \tag{3.19}$$

$$V^i = \frac{h\left(z^i\right)P + h\left(z^L\right)\left(\frac{1-\sigma}{n}\right)P - z^i}{r + \sum_{j=1}^{n} h\left(z^j\right) + h\left(z^L\right)} - F \tag{3.20}$$

Each entrant chooses its optimal R&D investments z^i, after having observed the investments of the incumbent (z^L). The first order condition of entrant i is:

$$\frac{\partial V^i}{\partial z^i}=\left.\begin{array}{l}\left[h'(z^i)P-1\right]\left[r+\sum_{j=1}^{n}h(z^j)+h(z^L)\right]\\-\left[h'(z^i)\right]\left[h(z^i)P+h(z^L)\left(\frac{1-\sigma}{n}\right)P-z^i\right]\end{array}\right/\left[r+\sum_{j=1}^{n}h(z^j)+h(z^L)\right]^2=0 \tag{3.21}$$

R&D investments of the entrants are the same in a symmetric equilibrium, z^i=z for all i. Thus:

$$\phi^i=\left[h'(z)P-1\right]\left[r+nh(z)+h(z^L)\right]-\left[h'(z)\right]\left[h(z)P+h(z^L)\left(\frac{1-\sigma}{n}\right)P-z\right]=0 \tag{3.22}$$

In the first stage, the incumbent decides on its profit maximizing R&D investments z^L:

$$\frac{\partial V^L}{\partial z^L}=\left.\begin{array}{l}\left[h'(z^L)\sigma P-1\right]\left[r+nh(z)+h(z^L)\right]\\-\left[h'(z^L)+\frac{\partial(nh(z))}{\partial z^L}\right]\left[h(z^L)P+\pi-z^L\right]\end{array}\right/\left[r+nh(z)+h(z^L)\right]^2=0 \tag{3.23}$$

or equivalently:

$$\phi^L=\left[h'(z^L)\sigma P-1\right]\left[r+nh(z)+h(z^L)\right]-\left[h'(z^L)+\frac{\partial(nh(z))}{\partial z^L}\right]\left[h(z^L)P+\pi-z^L\right]=0 \tag{3.24}$$

Now, define the following function[52]:

$$g_{A1}(x)=\left[h'(x)\sigma P-1\right]\left[r+nh(z)+h(z^L)\right]-\psi_{A1}\left[h(x)\sigma P+\pi-x\right] \tag{3.25}$$

with $g_{A1}(z^L)=0$,

$g'_{A1}(x)=\left.\frac{\partial\phi^L}{\partial z^L}\right|_{z^L=x}-h'(x)\left(h'(x)\sigma P-1\right)<0$ and

$\psi_{A1}=h'(x)+\left.\frac{\partial(nh(z))}{\partial z^L}\right|_{z^L=x}$.

Combining (3.22) and (3.25) and evaluating in x=z,

$$g_{A1}(z)=\begin{array}{l}-h'(z)(1-\sigma)P\left(r+nh(z)+h(z^L)\right)\\-\psi_{A1}\left[h(z)\sigma P+\pi-z\right]\\+h'(z)\left[h(z)\sigma P+h(z^L)\left(\frac{1-\sigma}{n}\right)P-z\right]\end{array} \tag{3.26}$$

The sign of (3.26) drives the comparison of z and z^L.

[52] The subscript A1 refers to the asymmetric reward sharing scenario A1.

3.4.2. Exogenous entry

In this section, the comparative statics of and the comparison between the incumbent's and the entrants' efforts are detailed for patent races with exogenous entry and reward sharing scenario A1 (see table 3.1).

3.4.2.1. Comparative statics

The impact of the different parameters on the R&D investments of the incumbent and the entrants are analogous to the symmetric reward sharing patent races with exogenous entry, see Table 3.4. Note that an increase in reward sharing (thus a lower value for σ) also reduces the investments of the entrants, although a winning entrant never shares. However, entrants' investments are far less sensitive to a change in σ than the investments of the incumbent.

$\frac{\partial x^L}{\partial \sigma} > 0$	$\frac{\partial x^L}{\partial n} > 0$	$\frac{\partial x^L}{\partial P} > 0$	$\frac{\partial x^L}{\partial F} = 0$	$\frac{\partial x^L}{\partial \pi} < 0$	$\frac{\partial x^L}{\partial r} > 0$
$\frac{\partial x}{\partial \sigma} > 0$	$\frac{\partial x^L}{\partial n} > 0$	$\frac{\partial x}{\partial P} > 0$	$\frac{\partial x}{\partial F} = 0$	$\frac{\partial x}{\partial \pi} < 0$	$\frac{\partial x}{\partial r} > 0$

Table 3.4. Comparative statics in the asymmetric reward sharing patent race A1 with exogenous entry.

3.4.2.2. Comparison of R&D investments of the incumbent and the entrants

With exogenous entry and asymmetric reward sharing A1 (a winning entrant takes it all but a winning incumbent shares), it is not straightforward to conclude from (3.24) whether the incumbent invests more or less in R&D than the entrants, as the sign of $g_A(z)$ is unclear[53]. After all, the first two terms of (3.26) are negative while the third term is positive and it is not clear which term dominates. Numerical simulations indicate however that the sign of $g_{A1}(z)$ is negative for all values of σ, thus entrants always invest more than the incumbent. This tendency is formalized in Proposition 3.3.

Proposition 3.3. In a patent race with exogenous entry and asymmetric market sharing A1, in which a winning incumbent shares with losing entrants but a winning entrant takes it all, an entrant always invests more than the incumbent, for all possible values of the market sharing parameter σ.

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[53] When σ=1, $g_{A1}(z)\big|_{\sigma=1} = -\frac{\partial\left(n \times h(z)\right)}{\partial z^L}\left[h(z)P + \pi - z\right] - h'(z)\pi < 0$, see Reinganum (1985).

Indeed, when there is winner-takes-all (σ=1), an entrant invests more than the incumbent. As already mentioned before, the incumbent reduces its efforts to make sure the entrants lower their efforts as well (strategic complementarity[54]), by which the incumbent extends the lifespan of its current patent. However, the entrants have lower incentives to shrink their investments as they do not enjoy a current stream of profits. Now, introducing reward sharing between a winning incumbent and losing entrants further reduces the R&D investments of the incumbent compared to entrants' efforts. So, the entrants always invest more than the incumbent in this specific reward sharing scenario. Consequently, technological leapfrogging tends to be the rule. Moreover, the larger the degree of reward sharing is, the more likely technological leapfrogging is. Note that technological leapfrogging here results in a monopoly position for the winning entrant.

Although he still has a chance of winning the race, it could be in the interest of the incumbent not to enter the race for a new product or a new technology, especially when the degree of market sharing is large. Indeed, firstly, for all values of σ, there is a higher probability that one of the entrants wins the race. Secondly, if the incumbent would win the race, part of the prize is snatched away by the losing entrants. For example, as mentioned in the introduction, EMI could only benefit for a short time period from its patent on the full body scanners as more experienced firms (in the medical equipment industry) entered and quickly controlled the whole market. Maybe, EMI could have been better off when it would not have raced for the bull body scanner but, instead, would have looked for other business opportunities.

The tendencies described here were also found in a strategic investment game with leaders and followers, no uncertainty, asymmetric spillovers and exogenous entry (section 2.4.2 or Vandekerckhove and De Bondt, 2008). Large spillovers from leaders to followers may result in lower investments of leaders compared to followers, even though large efforts of leaders could improve their subsequent Stackelberg profits. Figure 3.3 provides some graphical illustrations.

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[54] Indeed, simulations indicate that $\frac{\partial z}{\partial z^L} > 0$ for all possible values of σ.

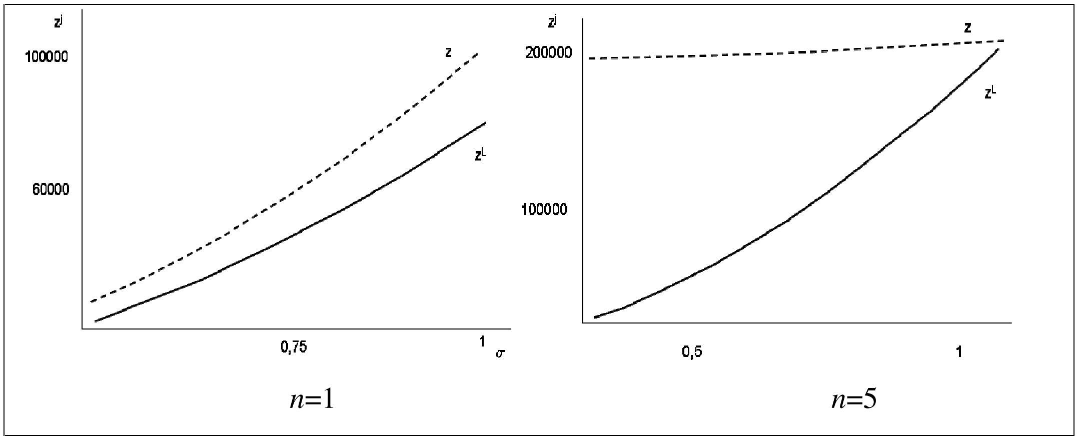

Figure 3.3. Asymmetric reward sharing A1 with exogenous entry. R&D investments of the incumbent and an entrant in function of σ, with P=1000, F=10, r=0.10, π=0, $h(x)=\sqrt{x}$, n=1 and n=5. The full line represents the investments of the incumbent (z^L) and the dashed line represents the investments of an entrant (z).

3.4.3. Endogenous entry

In the asymmetric patent race A1 with free entry, the zero profit condition states that:

$$ZPC_{A1}=h(z)P+h\left(z^L\right)\left(\frac{1-\sigma}{n}\right)P-z-F\left[r+nh(z)+h\left(z^L\right)\right]=0 \tag{3.27}$$

From this zero profit condition, the equilibrium number of entrants, n^*, can be calculated and this equilibrium number of entrants is negatively related with the investments of the incumbents. Moreover, combining (3.22) and (3.27) results in:

$$h'(z)(P-F)=1 \tag{3.28}$$

From (3.28), the R&D investments of each of the entrants, z, can be derived and, as was the case with symmetric reward sharing, the R&D investments of the entrants do not depend on the R&D investments of the incumbent and are also independent of r and π. Moreover, in this specific case, z is also independent of the sharing parameter σ.

The zero profit condition of the entrants (3.27) can be used to calculate $\left.\frac{\partial(nh(z))}{\partial z^L}\right|_{z^L=x}$ (for details, see the appendix of this chapter):

$$\left.\frac{\partial(nh(z))}{\partial z^L}\right|_{z^L=x}=\frac{h'(x)\left[\left(\frac{1-\sigma}{n}\right)P-F\right]}{\frac{h(x)}{h(z)}\left(\frac{1-\sigma}{n^2}\right)P+F}. \tag{3.29}$$

Substituting (3.29) in (3.26) and evaluating in x=z results in:

$$-h'(z)(1-\sigma)P\left(r+nh(z)+h\left(z^L\right)\right)$$

$$g_{A1}(z)=-\left[h'(z)+\frac{h'\left(z^L\right)\left[\left(\frac{1-\sigma}{n}\right)P-F\right]}{\frac{h\left(z^L\right)}{h(z)}\left(\frac{1-\sigma}{n^2}\right)P+F}\right]\left[h(z)\sigma P+\pi-z\right] \quad (3.30)$$

$$+h'(z)\left[h(z)\sigma P+h\left(z^L\right)\left(\frac{1-\sigma}{n}\right)P-z\right]$$

3.4.3.1. Comparative Statics

To continue, the comparative statics of the R&D investments of the incumbent and the entrants are dealt with and summarized in Table 3.5.

$\frac{\partial x^L}{\partial \sigma}>0$	$\frac{\partial x^L}{\partial P}>0$	$\frac{\partial x^L}{\partial F}=0$ with σ=1 $\frac{\partial x^L}{\partial F}<0$ with σ<1	$\frac{\partial x^L}{\partial \pi}=0$ with σ=1 $\frac{\partial x^L}{\partial \pi}<0$ with σ<1	$\frac{\partial x^L}{\partial r}=0$
$\frac{\partial x}{\partial \sigma}=0$	$\frac{\partial x}{\partial P}>0$	$\frac{\partial x}{\partial F}<0$	$\frac{\partial x}{\partial \pi}=0$	$\frac{\partial x}{\partial r}=0$
$\frac{\partial n^*}{\partial \sigma}<0$	$\frac{\partial n^*}{\partial P}>0$	$\frac{\partial n^*}{\partial F}<0$	$\frac{\partial n^*}{\partial \pi}=0$ with σ=1 $\frac{\partial n^*}{\partial \pi}>0$ with σ<1	$\frac{\partial n^*}{\partial r}=0$

Table 3.5. Comparative statics in the asymmetric reward sharing patent race A1 with endogenous entry.

Comparative statics of the investments of the incumbent in patent races with endogenous entry and asymmetric reward sharing A1 are the same as with symmetric reward sharing. Thus, the incumbent's efforts are increasing in σ. Furthermore, current profits reduce the incumbent's investment incentives when there is reward sharing. The tendencies of the equilibrium number of entrants are also the same as in the case of symmetric reward sharing.

However, the investments of the entrants are independent of the market sharing parameter σ (see (3.28)). Entrants do not reduce their R&D investments when there is reward sharing in case of a winning incumbent. After all, entrants do not share when they win, by which their investments are not influenced by changes in σ when there is free entry.

Current profits and the incumbent's R&D investments

Here, the impact of the current profits on the investments of the incumbent depends again on the value of σ. When there is winner-takes-all (σ=1), the investments of the incumbent are unaffected by a change in π (Etro, 2004). However, when there is some reward sharing (σ<1), the investments of the incumbent decrease when π increases. This tendency can be understood by considering the zero profit condition (3.27), which is now rewritten as:

$$h(z)P + h\left(z^L\right)\left(\frac{1-\sigma}{n}\right)P - z = F\left[r + nh(z) + h\left(z^L\right)\right] \qquad (3.31)$$

When the incumbent cuts down his efforts, it is known that the number of entrants will rise but the investments of each entrant remain unaffected. Consequently, the left hand side of (3.31) decreases by which the right hand side of (3.31) needs to decline as well. Thus, the incumbent can lower the aggregate probability of innovation by reducing his R&D investments. Of course, the more valuable the current patent is, the more incentives the incumbent has to cut down his efforts.

3.4.3.2. Comparison of R&D investments of the incumbent and the entrants

Analyzing the sign of (3.30) allows comparing the R&D investments of the incumbent and the entrants. For values of σ<1, however, the sign of (3.30) is unclear as the first and second terms are negative while the third term is positive and it is not clear which term dominates[55]. Numerical simulations indicate that, for π=0, the sign of (3.30) can be positive (for high values of σ) or negative (for small values of σ). It is thus possible that, with endogenous entry, the entrants invest more in R&D compared to the incumbent, see Proposition 3.4. For a graphical illustration, see Figure 3.4.

Proposition 3.4. In a patent race with asymmetric market sharing A1, in which there is only sharing when the incumbent wins, and endogenous entry, the incumbent invests more than entrants when there is a small degree of market sharing (high value

[55] For For σ=1, the winner-takes-all result with endogenous entry of Etro (2004) is obtained. Indeed $g_A(z)\big|_{\sigma=1} = h'(z)\left[h(z)P - z\right]$ and the sign of this expression is always positive. So the incumbent invests more than each of the entrants.

of σ) while the entrants invest more than the incumbent when there is a large degree of market sharing (low value of σ).

With winner-takes-all, the only incentive for the incumbent is to win the race and its incentives to do so are higher than entrants' incentives. However, losing part of the new market by the incumbent in the asymmetric patent race A1 with endogenous entry tends to discourage its efforts in two different ways. Firstly, the sharing of rewards in se has a negative impact on the incentives of the incumbent. After all, the more the entrants can benefit from the innovation of the incumbent, the less the incumbent is willing to invest in R&D. Secondly, this negative effect on R&D investments is strengthened by the fact that the incumbent can lower the aggregate probability of innovation (and hence extend the lifespan of the current patent) by lowering its investments.

All in all, the R&D investments of the incumbent decrease when there is reward sharing between the winning incumbent and the losing entrants. When the reward sharing is sufficiently large, the incumbent's R&D efforts can be reduced that much by which Etro's asymmetry (2004) is reversed in the advantage of the entrants, who then invest more in R&D than the incumbent. Consequently, technological leapfrogging tends to be more likely in patent races with endogenous entry when the losing entrants can easily steal a large part of the fruits of the incumbent's innovation.

An analogous tendency is observed in strategic investment games in which R&D expenses decrease when the spillover increases. This is reminiscent of the public good character of R&D. The same is observed here. More specifically, in this case, there is only sharing when the incumbent wins, which can be interpreted as a spillover from the leader to the followers. When the reward sharing is sufficiently high (low value of σ), the reduction of the incumbent's investments is of such an extent (compared to winner-takes-all) that investments of entrants exceed the investments of the incumbent.

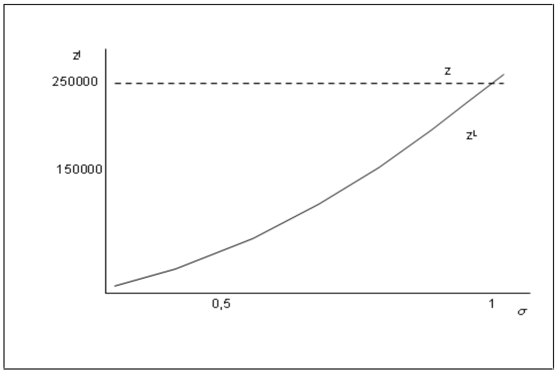

Figure 3.4. Asymmetric reward sharing A1 with endogenous entry. R&D investments of the incumbent and an entrant in function of σ, with P=1000, F=10, r=0.10, π=0, $h(x)=\sqrt{x}$. The full line represents the investments of the incumbent (z^L) and the dashed line represents the investments of an entrant (z).

3.5. Asymmetric reward sharing A2: winning leader takes it all

In this section, patent races with the second asymmetric reward sharing scenario (A2) are analyzed. Here, a winning entrant shares with the other entrants, while a winning incumbent takes it all. After solving the game in general, some comparative statics of the R&D investments of the incumbent and the entrants are detailed, followed by a comparison of their efforts.

3.5.1. Solutions

Substituting the payoffs of case A2 in the expected profit functions of the incumbent (3.3) and the entrants (3.4), yields:

$$V^L = \frac{h\left(z^L\right)P + \pi - z^L}{r + \sum_{j=1}^{n} h\left(z^j\right) + h\left(z^L\right)} - F \tag{3.32}$$

$$V^i = \frac{h\left(z^i\right)\sigma P + \sum_{\substack{j=1 \\ j\neq i}}^{n} h\left(z^j\right)\left(\frac{1-\sigma}{n-1}\right)P - z^i}{r + \sum_{j=1}^{n} h\left(z^j\right) + h\left(z^L\right)} - F \tag{3.33}$$

For each of the n entrants, the first order condition needs to be satisfied:

$$\frac{\partial V^i}{\partial z^i} = \left. \begin{array}{l} \left[h'\left(z^i\right)\sigma P - 1\right]\left[r + \sum_{j=1}^{n} h\left(z^j\right) + h\left(z^L\right)\right] \\ -\left[h'\left(z^i\right)\right]\left[h\left(z^i\right)\sigma P + \sum_{\substack{j=1 \\ j\neq i}}^{n} h\left(z^j\right)\left(\frac{1-\sigma}{n-1}\right)P - z^i\right] \end{array} \right/ \left[r + \sum_{j=1}^{n} h\left(z^j\right) + h\left(z^L\right)\right]^2 = 0 \tag{3.34}$$

In a symmetric equilibrium, all entrants spend the same amount of resources on R&D. So, with z^i=z for all i:

$$\varphi^i = \left[h'(z)\sigma P - 1\right]\left[r + nh(z) + h\left(z^L\right)\right] - \left[h'(z)\right]\left[h(z)P - z\right] = 0 \tag{3.35}$$

The incumbent maximizes its profits by choosing z^L:

$$\frac{\partial V^L}{\partial z^L} = \frac{\left[h'(z^L)P-1\right]\left[r+nh(z)+h(z^L)\right] - \left[h'(z^L)+\frac{\partial(nh(z))}{\partial z^L}\right]\left[h(z^L)P+\pi-z^L\right]}{\left[r+nh(z)+h(z^L)\right]^2} = 0 \tag{3.36}$$

or equivalently:

$$\phi^L = \left[h'(z^L)P-1\right]\left[r+nh(z)+h(z^L)\right] - \left[h'(z^L)+\frac{\partial(nh(z))}{\partial z^L}\right]\left[h(z^L)P+\pi-z^L\right] = 0 \tag{3.37}$$

Now define the following function[56]:

$$g_{A2}(x) = \left[h'(x)P-1\right]\left[r+nh(z)+h(z^L)\right] - \psi_{A2}\left[h(x)P+\pi-x\right] \tag{3.38}$$

with $g_{A2}(z^L)=0$,

$$\psi_{A2} = h'(x) + \left.\frac{\partial(nh(z))}{\partial z^L}\right|_{z^L=x} \text{ and}$$

$$g_{A2}'(x) = \left.\frac{\partial \phi^L}{\partial z^L}\right|_{z^L=x} - h'(z)\left(h'(z^L)P-1\right) < 0 .$$

The sign of (3.38) determines the comparison of the R&D investments of the incumbent and the entrants.

3.5.2. Exogenous entry

3.5.2.1. Comparative statics

The comparative statics of the R&D investments of the incumbent and the entrants are analogous to the two other patent races with exogenous entry. Both the incumbent's and the entrants' investments are increasing in the sharing parameter σ. Note however that the incumbent's investments are less sensitive to a change in σ than the entrants' investments. For completeness, Table 3.6 summarizes the tendencies for the asymmetric reward sharing patent race with exogenous entry.

$\frac{\partial x^L}{\partial \sigma} > 0$	$\frac{\partial x^L}{\partial n} > 0$	$\frac{\partial x^L}{\partial P} > 0$	$\frac{\partial x^L}{\partial F} = 0$	$\frac{\partial x^L}{\partial \pi} < 0$	$\frac{\partial x^L}{\partial r} > 0$
$\frac{\partial x}{\partial \sigma} > 0$	$\frac{\partial x^L}{\partial n} > 0$	$\frac{\partial x}{\partial P} > 0$	$\frac{\partial x}{\partial F} = 0$	$\frac{\partial x}{\partial \pi} < 0$	$\frac{\partial x}{\partial r} > 0$

Table 3.6. Comparative statics in the asymmetric reward sharing patent race A2 with exogenous entry.

[56] Subscript A2 refers to the asymmetric reward sharing scenario A2.

3.5.2.1. Comparison the R&D investments of the incumbent and the entrants

Numerical simulations are necessary to compare the investments of the incumbent and the entrants. After all, the sign of (3.38) is unclear[57] as the first term is positive while the second term is negative. These simulations indicate that the sign of $g_{A2}(z)$ can be negative (for high values of σ) and positive (for small values of σ). In other words, when there is sufficient reward sharing, Reinganum's comparison of the investments of the incumbent and the entrants is reversed as the incumbent invests then more than each entrant, see Proposition 3.5 and Figure 3.5. However, when the incumbent's current profits are very high, the entrants always invest more than the incumbent.

Proposition 3.5. In a patent race with asymmetric market sharing (A2), in which a winning entrant shares with the other losing entrants, and with exogenous entry, an entrant invests more than the incumbent when there is a small degree of market sharing (high values of σ) while the incumbent invests more than each entrant when there is a large degree of market sharing (small values of σ). For sufficiently high current profits of the incumbent, an entrant always invests more than the incumbent.

With winner-takes-all, the incumbent always invests less than the entrants. However, when there is reward sharing, the incumbent's and the entrants' investments are reduced compared to the winner-takes-all setting but followers' incentives are reduced more when there is a higher degree of reward sharing. This tendency can be compared with the negative impact of the follower-specific spillover among competing followers in a strategic investment game with leaders and followers (see section 2.3.2). When the reward sharing is sufficiently large, its negative impact on entrants' investments offsets the negative impact of the current patent on the incumbent's investments[58] and explains why the incumbent may invest more than the entrants when reward sharing is sufficiently large. Reinganum's (1985) finding can thus be altered when the value of σ is sufficiently small. Note that, for very large values of

[57] For σ=1, it is known that (by making use of the first order condition of the followers):

$g_B(z)\big|_{\sigma=1} = -\frac{\partial(nh(z))}{\partial z^L}\left[h(z)P+\pi-z\right]-h'(z)\pi<0$, cfr Reinganum (1985).

[58] Indeed, simulations indicate indeed that $\frac{\partial z}{\partial z^L}>0$ for all possible values of σ.

the current profits of the incumbent, the entrants always invest more than the incumbent.

Thus, when the reward sharing among entrants is large enough, the incumbent is more likely to win the race by which there is a higher likelihood of leadership persistency. Here, leadership persistence equals monopoly persistence as a winning incumbent does not share and thus captures the total value of the patent.

Before entrants enter this kind of patent races, a good assessment of the reward sharing parameter might be valuable. When entrants can protect their innovations effectively (and reward sharing is small), it is worthwhile for the entrants to give it a try. However, when the reward sharing is too large, the investments of the incumbent are higher by which an entrant is less likely to win the race compared to the incumbent. Moreover, if an entrant wins, a large part of the prize is then shared with other entrants. Thus, if reward sharing is too large, improving on protection instruments for innovations or not entering the race at all could be in the interest of the entrants.

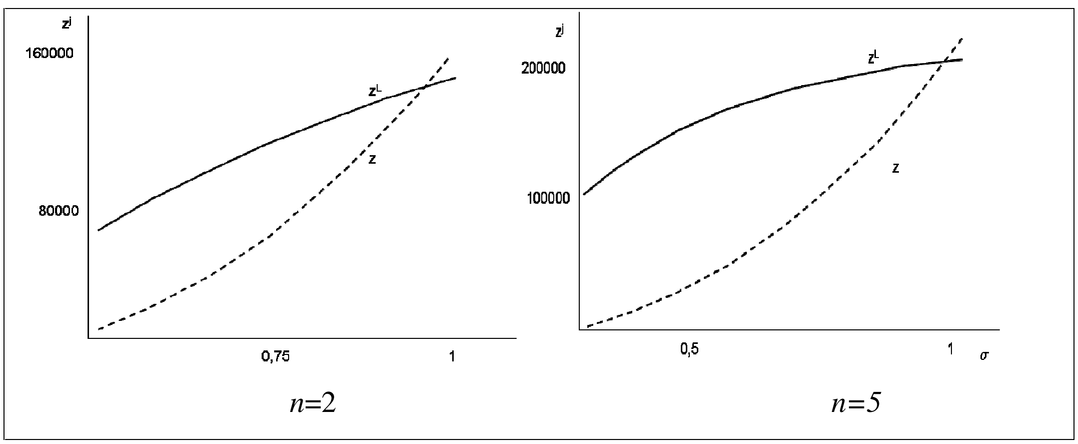

Figure 3.5. Asymmetric reward sharing A2 with exogenous entry. R&D investments of the incumbent and an entrant in function of σ, with P=1000, F=10, r=0.10, π=0, $h(x)=\sqrt{x}$, n=2 and n=5. The full line represents the investments of the incumbent (z^L) and the dashed line represents the investments of an entrant (z).

3.5.3. Endogenous entry

With endogenous entry, the zero profit condition states:

$$ZPC_{A2} = h(z)P - z - F\left[r + nh(z) + h\left(z^L\right)\right] = 0 \tag{3.39}$$

This zero profit condition determines the equilibrium number of entrants n^*, which is decreasing in the investments of the incumbent. The combination of the zero profit condition and (3.35) yields:

$$h'(z)(\sigma P - F) = 1 \tag{3.40}$$

From (3.40), the investments of the entrants z can be derived and it is clear that z, just like in the two other patent races with endogenous entry, does not depend on z^L. However, z depends on the degree of market sharing and it can easily be verified that z is an increasing function of the sharing parameter σ. Moreover, z is also independent of r and π.

By using the zero profit condition of the entrants, $\left.\frac{\partial(nh(z))}{\partial z^L}\right|_{z^L=x}$ can be calculated (see appendix): $\left.\frac{\partial(nh(z))}{\partial z^L}\right|_{z^L=x} = -h'(x)$. Substituting this expression in (3.38), evaluated in x=z, results in:

$$g_{A2}(z) = \left[h'(z)P - 1\right] \times \left[r + nh(z) + h\left(z^L\right)\right] \tag{3.41}$$

Moreover, as $\frac{\partial(nh(z))}{\partial z^L} = -h'\left(z^L\right)$ (see appendix), the following condition on the R&D investments for the incumbent prevails, by using (3.37):

$$h'\left(z^L\right)P = 1 \tag{3.42}$$

Equation (3.39) shows that the R&D investments of the incumbent are only dependent on and increasing in the value of the discovery P.

3.5.3.1. Comparative statics

The comparative statics of the efforts of the incumbent and the entrants can easily be derived using (3.40) and (3.42) and are summarized in table 3.7. As indicated by (3.42), the incumbent's investments are independent of the market sharing parameter σ, as a winning incumbent takes it all. R&D investments of the incumbent are of course increasing in the value of the discovery P, while being independent of all the other remaining parameters. Investments of entrants are increasing in σ and increasing in P, while decreasing in the fixed costs F (see 3.40). Tendencies of the equilibrium number of entrants are the same as with symmetric reward sharing.

$\frac{\partial x^L}{\partial \sigma} = 0$	$\frac{\partial x^L}{\partial P} > 0$	$\frac{\partial x^L}{\partial F} = 0$	$\frac{\partial x^L}{\partial \pi} = 0$	$\frac{\partial x^L}{\partial r} = 0$
$\frac{\partial x}{\partial \sigma} > 0$	$\frac{\partial x}{\partial P} > 0$	$\frac{\partial x}{\partial F} < 0$	$\frac{\partial x}{\partial \pi} = 0$	$\frac{\partial x}{\partial r} = 0$
$\frac{\partial n^*}{\partial \sigma} < 0$	$\frac{\partial n^*}{\partial P} > 0$	$\frac{\partial n^*}{\partial F} < 0$	$\frac{\partial n^*}{\partial \pi} = 0$	$\frac{\partial n^*}{\partial r} = 0$

Table 3.7. Comparative statics in the asymmetric reward sharing patent race A2 with endogenous entry.

Current profits and the incumbent's R&D investments

Equation (3.42) states that the incumbent's R&D investments are never affected by a change in the current profits. Indeed, for each degree of reward sharing, the zero profit condition states that:

$$h(z)P - z = F\left[r + nh(z) + h\left(z^L\right)\right] \tag{3.43}$$

From this expression, it is clear that the incumbent can not alter the aggregate probability of innovation by lowering its R&D efforts. Consequently, the level of current profits will not influence the R&D investment decision of the incumbent.

3.5.3.2. Comparison of the R&D investments of the incumbent and the entrants

The comparison of the R&D investments of the incumbent and each entrant is straightforward as the sign of (3.38) is always positive. The finding of Etro (2004) appears to be robust for the introduction of this specific type of asymmetric reward sharing, see Proposition 3.6 and Figure 3.6.

Proposition 3.6. In a patent race with endogenous entry and with asymmetric reward sharing A2, in which a winning entrant shares with the losing entrants, the incumbent always invests more than the entrants.

The intuition of this result is straightforward. It has already been mentioned that with winner-takes-all, the incumbent invests more than each of the entrants as the only ambition of the incumbent is to win the race. Now, reward sharing further discourages R&D investments of the entrants, while the incumbent's investments are unaffected by a change in the reward sharing parameter. Moreover, the current profits have no impact on the incumbent's incentives. Consequently, the incumbent always invests more than the entrants by which leadership persistence, which equals monopoly persistence here, is most likely. Furthermore, the larger the reward sharing is (or the smaller σ), the less likely an entrant is to win the race[59]. Figure 3.6 illustrates.

Just like with exogenous entry, the entrants should again think twice before entering the race. First, their individual chances to win the race are smaller than the incumbent, by which there is a high likelihood that their R&D investments will be lost. Secondly, in the less likely case that an entrant would win the race, the winner needs to share the prize with the other entrants.

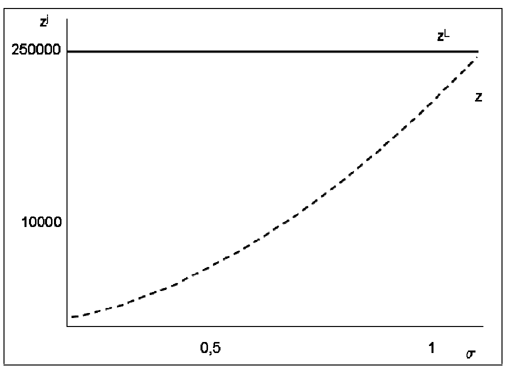

Figure 3.6. Asymmetric reward sharing A2 with endogenous entry. R&D investments of the incumbent and an entrant in function of σ, with V=1000, F=10, r=0.10, π=0 and $h(x)=\sqrt{x}$. The full line represents the investments of the incumbent (z^L) and the dashed line represents the investments of each entrant (z).

3.6. Expected profits of the incumbent and entrants

In this section, the expected profits of the incumbent and the entrants are analyzed. For patent races with exogenous entry, comparative statics are provided and the incumbent's and the entrants' profits are compared. For patent races with endogenous entry, the analysis limits itself to the comparative statics of the expected profits of the incumbent. After all, the expected profits of the incumbent are, by definition, always higher than the expected profits of the entrants, as expected profits of the incumbent

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[59] It is also possible to derive Proposition 3.4 by combining (3.40) and (3.42).
From (3.40) and (3.42), it is known that

$$h'\left(z^L\right)=\frac{1}{P} \quad \text{and} \quad h'(z)=\frac{1}{\sigma P-F}$$

So, $h'\left(z^L\right)<h'(z)$. Using the properties of the *h(.)* function, it is clear that $z^L>z$.

are assumed to be positive (positive profit condition) and followers' expected profits equal zero (zero profit condition).

3.6.1. Comparative statics with exogenous entry

The comparative statics of the expected profits of the incumbent and the entrants in patent races with exogenous entry are presented in Tables 3.8a and 3.8b. Here, only a description of the tendencies is provided. The reason is that, with the available information, it is hard to predict and analyze comparative statics of expected profits. Consider for example a change in the sharing parameter σ. From the previous sections, it is known that, with exogenous entry, an increase in the reward sharing parameter σ encourages investments of the incumbent and the entrants. However, this knowledge is not sufficient to predict the effect of an increase in the sharing parameter on expected profits. Firstly, it is not known whether these higher investments increase or reduce the expected total R&D costs. After all, due to the higher investments, there is an earlier expected time of innovation but it is not clear whether this earlier innovation date compensates for the larger R&D investments per time unit. The impact of an increase in σ on total expected R&D costs is thus not straightforward. Secondly, it is of course impossible that, by increasing their investments, both the incumbent and the entrants have a higher probability of winning the race. However, how the probability of innovation by the incumbent changes vis-à-vis the probability of innovation by one of the entrants is not known.

In all three reward sharing scenarios, an increase in the number of entrants negatively affects expected profits. After all, the more entrants there are, the more competitive the racing environment is by which expected profits are reduced. To continue, a higher private patent value of the innovation always has a positive effect on the expected profits of the incumbent and the entrants. To continue, the current profits have a positive effect while the interest rate has a negative effect on expected profits of the incumbent and the entrants.

With symmetric reward sharing, expected profits of the incumbent and the entrants decrease in σ. In patent races with asymmetric sharing A1, there is still a negative impact of σ on the expected profits of the entrants but expected incumbent's profits are positively affected by σ. When the asymmetric sharing takes the form of A2, the incumbent's expected profits are decreasing in σ and entrants' expected profits are increasing in σ when σ is small, while there is a negative effect of σ when σ is large.

$\frac{\partial V^L}{\partial n} < 0$	$\frac{\partial V^L}{\partial P} > 0$	$\frac{\partial V^L}{\partial F} < 0$	$\frac{\partial V^L}{\partial \pi} > 0$	$\frac{\partial V^L}{\partial r} < 0$
$\frac{\partial V}{\partial n} < 0$	$\frac{\partial V}{\partial P} > 0$	$\frac{\partial V}{\partial F} < 0$	$\frac{\partial V}{\partial \pi} > 0$	$\frac{\partial V}{\partial r} < 0$

Table 3.8a. Impact of n, P, F, π and r on expected profits of the incumbent and the entrants in patent races with exogenous entry and all three types of reward sharing (S, A1 and A2).

Symmetric Sharing S	Asymmetric Sharing A1	Asymmetric Sharing A2
$\frac{\partial V^L}{\partial \sigma} < 0$	$\frac{\partial V^L}{\partial \sigma} > 0$	$\frac{\partial V^L}{\partial \sigma} < 0$
$\frac{\partial V}{\partial \sigma} < 0$	$\frac{\partial V}{\partial \sigma} < 0$	$\frac{\partial V}{\partial \sigma} > 0$ for small σ $\frac{\partial V}{\partial \sigma} < 0$ for large σ

Table 3.8b. Impact of σ on the expected profits of the incumbent and the entrants in patent races with exogenous entry.

3.6.2. Comparison of expected profits of the incumbent and the entrants with exogenous entry

Expected profits of the incumbent and the entrants are only compared for π=0. After all, sufficiently large current profits can always result in higher expected profits for the incumbent, even if σ=1. Numerical simulations are used. Proposition 3.7 summarizes.

Proposition 3.7. In patent races with exogenous entry, π=0 and reward sharing, entrants generally realize higher expected profits than the incumbent. However, with reward sharing among entrants (A2), the incumbent can realize higher expected profits compared to the entrants, provided that the reward sharing is large enough (thus a small value of σ).

According to Proposition 3.7, the entrants always enjoy second mover advantages when there is symmetric (S) or asymmetric reward sharing A1. This tendency is a generalization of the finding of Reinganum (1985) that entrants realize higher expected profits than the incumbent when there is winner-takes-all. As the entrants always invest more in R&D in these two scenarios, their probability of innovation is always higher compared to the incumbent's probability of innovation, which explains the higher expected profits of the entrants. This reasoning applies to all values of σ. When there is asymmetric reward sharing A2, the incumbent may benefit, in terms of expected profits, from moving first in the R&D stage. When the winning incumbent takes it all while the winning entrant needs to share with other entrants, it could be that the incumbent's expected profits are higher than the entrants' expected profits when σ is small enough (i.e. sufficient sharing of rewards). After all, when there is a large degree of reward sharing among entrants, R&D expenditures of the incumbent may be larger than investments of the entrants and first mover advantages may then prevail as the incumbent has then a higher probability of winning the race. Consequently, reward sharing can, in some specific cases, alter the prediction of Reinganum (1985). Figures 3.7a, 3.7b and 3.7c present some graphical presentations of the expected profits of the incumbent and the entrants as a function of σ.

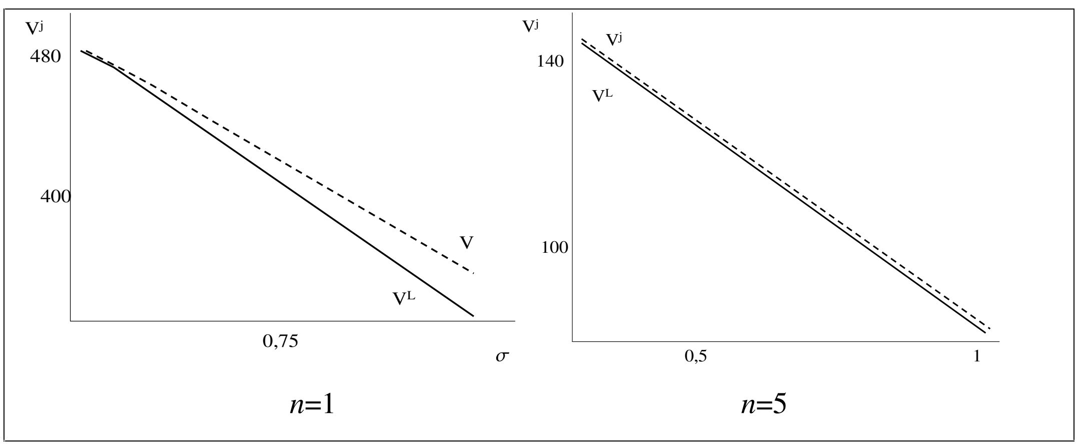

Figure 3.7a. Symmetric reward sharing with exogenous entry. Expected profits of the incumbent and an entrant in function of σ, with P=1000, F=10, r=0.10, π=0, $h(x)=\sqrt{x}$, n=1 and n=5. The full line represents the investments of the incumbent (z^L) and the dashed line represents the investments of an entrant (z).

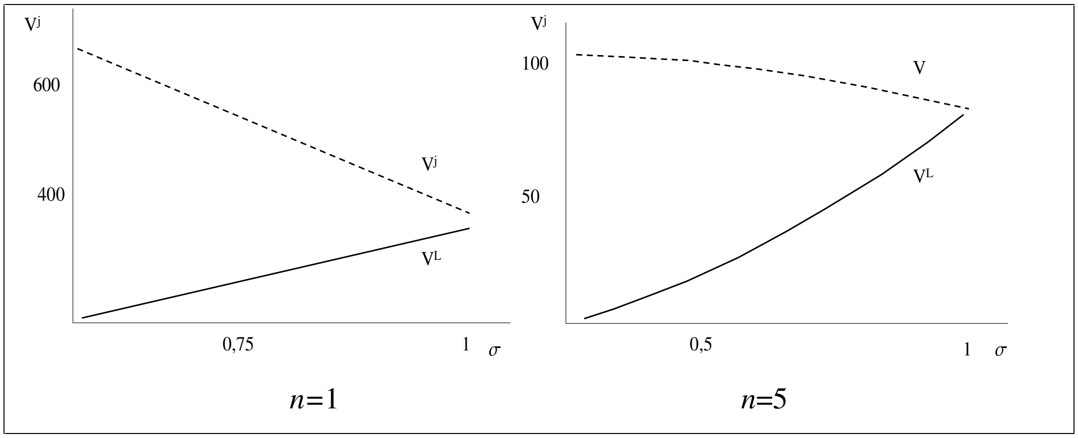

Figure 3.7b. Asymmetric reward sharing A1 with exogenous entry. Expected profits of the incumbent and an entrant in function of σ, with P=1000, F=10, r=0.10, π=0, $h(x)=\sqrt{x}$, n=1 and n=5. The full line represents the investments of the incumbent (z^L) and the dashed line represents the investments of an entrant (z).

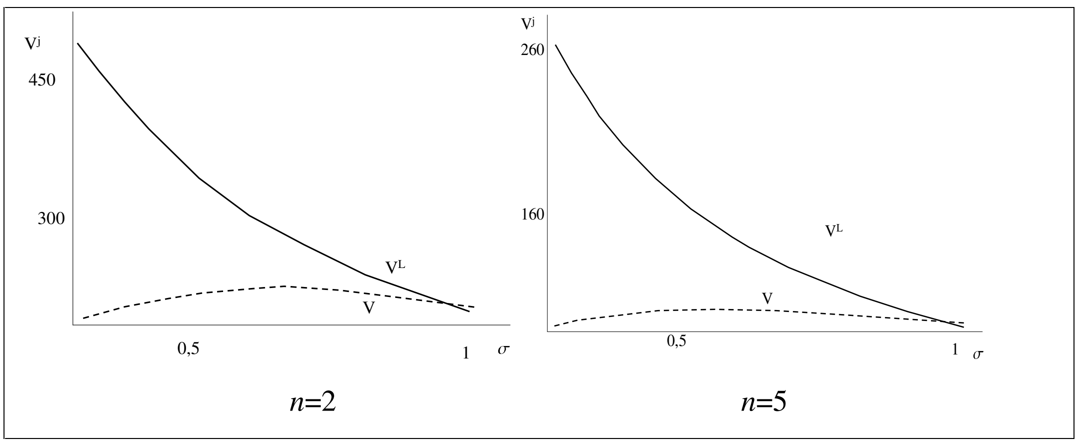

Figure 3.7c. Asymmetric reward sharing A2 with exogenous entry. Expected profits of the incumbent and an entrant in function of σ, with P=1000, F=10, r=0.10, π=0, $h(x)=\sqrt{x}$, n=2 and n=5. The full line represents the investments of the incumbent (z^L) and the dashed line represents the investments of an entrant (z).

3.6.3. Comparative statics with endogenous entry

With endogenous entry, it is, just like with exogenous entry, hard to predict and analyze the comparative statics of the expected profits of the incumbent. Again, it is for example difficult to assess the impact of a change in R&D investments on the expected value of total R&D costs. Therefore, this section is limited to only the description of the comparative statics. With endogenous entry (see Table 3.9) the expected profits of the incumbent are increasing in the market sharing parameter σ when there is symmetric sharing and asymmetric sharing A1. However, when there is asymmetric sharing A2, the expected profits of the incumbent are decreasing in σ. Another remarkable tendency is that the expected profits of the incumbent are decreasing in the value of the discovery P. To continue, the incumbent's expected profits are decreasing in the fixed cost F and the interest r, but increasing in the current profits π.

Symmetric Sharing S	$\frac{\partial V^L}{\partial \sigma} > 0$	$\frac{\partial V^L}{\partial P} < 0$	$\frac{\partial V^L}{\partial F} < 0$	$\frac{\partial V^L}{\partial \pi} > 0$	$\frac{\partial V^L}{\partial r} < 0$
Asymmetric Sharing A1	$\frac{\partial V^L}{\partial \sigma} > 0$	$\frac{\partial V^L}{\partial P} < 0$	$\frac{\partial V^L}{\partial F} < 0$	$\frac{\partial V^L}{\partial \pi} > 0$	$\frac{\partial V^L}{\partial r} < 0$
Asymmetric Sharing A2	$\frac{\partial V^L}{\partial \sigma} < 0$	$\frac{\partial V^L}{\partial P} < 0$	$\frac{\partial V^L}{\partial F} < 0$	$\frac{\partial V^L}{\partial \pi} > 0$	$\frac{\partial V^L}{\partial r} < 0$

Table 3.9. Impact of σ, P, F, π and r on expected profits of the incumbent in patent races with endogenous entry.

3.7. Social planner

In the last section of this study, R&D investments of the incumbent and the entrants are compared with the optimal investments from the social planner's point of view. The social planner maximizes total welfare, which equals the sum of producer and consumer surplus. Producer surplus is the sum of expected profits of the incumbent and the entrants. Consumer surplus is equal to the discounted value of the difference between the social value of the innovation and its private value. Indeed, the social value of an innovation is often higher than its private value. For example, Philipson and Jena (2006) estimate that innovators of the HIV/AIDS therapies, which entered the market from the late 1980s onwards, could only appropriate 5% of the social surplus. In dollar amounts, consumer surplus equaled approximately \$1,33 trillion while producer surplus only amounted to roughly \$63 billion.

Analytically, consumer and producer surplus are given by the following functions:

$$CS = \frac{\left[h\left(x_S^L\right) + \sum_{i=1}^{n} h\left(x_S^i\right)\right]\left[P^* - P\right]}{r + \sum_{j=1}^{n} h\left(x_S^j\right) + h\left(x_S^L\right)}, \text{ and} \tag{3.44}$$

$$PS = \frac{\left[V^L\left(x_S^L, x_S^i\right) + \sum_{i=1}^{n} V^i\left(x_S^L, x_S^i\right) + \pi - x_S^L - \sum_{i=1}^{n} x_S^i\right]}{r + \sum_{j=1}^{n} h\left(x_S^j\right) + h\left(x_S^L\right)} - (n+1)F, \tag{3.45}$$

with P^* indicating the social value of the innovation, and x_S^L and x_S^i the optimal investments of the incumbent and the entrants from the perspective of a social planner.

For all three reward sharing scenarios, inserting the expected profit functions[60] brings about the following analytical expression for producer surplus:

$$PS = \frac{\left[h\left(x_S^L\right)P + \sum_{i=1}^{n} h\left(x_S^i\right)P + \pi - x_S^L - \sum_{i=1}^{n} x_S^i \right]}{r + \sum_{i=1}^{n} h\left(x_S^i\right) + h\left(x_S^L\right)} - (n+1)F \ . \qquad (3.46)$$

Consequently, total surplus, as the sum of PS and CS, is given by the following expression:

$$TS = \frac{\left[h\left(x_S^L\right)P^* + \sum_{i=1}^{n} h\left(x_S^i\right)P^* + \pi - x_S^L - \sum_{i=1}^{n} x_S^i \right]}{r + \sum_{i=1}^{n} h\left(x_S^j\right) + h\left(x_S^L\right)} - (n+1)F \ . \qquad (3.47)$$

From (3.47), it is clear that total surplus is not dependent on the reward sharing parameter σ. In other words, the social planner does not care if and how rewards of an innovation are shared among the winner and the losers of the race[61].

Consequently, with exogenous entry, the only ambition of the social planner is to choose the optimal investments of the incumbent and the entrants. When there is free entry, the social planner moreover has to decide on the optimal number of entrants n^*. More precisely, the objective functions for the social planner are the following:

for exogenous entry: $$\underset{x_S}{\text{Max}}\, TS = \frac{(n+1)\left[h(x)P^* + \pi - x\right]}{r + (n+1)h(x)} - (n+1)F \text{ and } \qquad (3.48)$$

for endogenous entry: $$\underset{x_S,n}{\text{Max}}\, TS = \frac{(n+1)\left[h(x)P^* + \pi - x\right]}{r + (n+1)h(x)} - (n+1)F \ , \qquad (3.49)$$

with x_S the optimal investments of the incumbent and the entrants.

---

[60] The expected profit functions are given by (3.5) and (3.6) for the symmetric reward sharing scenario, by (3.19) and (3.20) for the asymmetric reward sharing scenario A1 and by (3.32) and (3.33) for the asymmetric reward sharing scenario A2.

[61] In the analysis here, the social value of the innovation P^* is determined exogenously. It could however be argued that the value of P^* depends on the degree of reward sharing. Indeed, if the winner takes it all, the winner becomes a monopolist while an oligopoly can result when there is reward sharing. As a monopoly results in higher prices, the social value P^* could be assumed to be higher when there is a larger degree of market sharing (thus a lower value for σ would then result in a higher value of P^*).

It turns out that, with exogenous entry, both the incumbent and the entrants always invest more in R&D than what is socially optimal. When entry is endogenous, the incumbent and the entrants also overinvest in R&D compared to the social optimum. Note that overinvestment in R&D by the incumbent and the entrants is most serious when there is winner-takes-all as in general, racing firms invest less in R&D when there is reward sharing[62]. Only when the social value of the innovation is sufficiently larger than the private value, it could be that both the incumbent and the entrants invest less than the socially optimal amount of R&D expenditures.

In addition, with endogenous entry, the problem of excessive R&D expenditures is further deteriorated as the number of firms entering the race exceeds the socially optimal number of entrants, provided that the social value does not exceed the private value too much.

These findings are in line with previous research. For example, Reinganum (1989) claims that the following tendency is true for patent races:

> *"The typical outcome of these comparisons [between models that compare noncooperative investment in research and development with cooperative investment or the surplus-maximizing result] is that aggregate expenditure on R&D is too high relative to the cooperative [or surplus-maximizing] optimum; there are too many firms and each invests too much."*

Consequently, the study shows that it can be in the government's interest to tax R&D in order to reduce private R&D investments[63]. This observation is similar to Li (2001) who argues that radical technological breakthroughs, i.e. sufficiently large quality improvements, should be taxed. Moreover, it is found here that the degree of taxation should depend on the degree of reward sharing in the industry, which is determined by the strength of patent protection.

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[62] With asymmetric reward sharing A1, only incumbent's R&D investments are reduced when σ decreases. With asymmetric reward sharing A2, only entrants are discouraged to invest in R&D when there is more reward sharing.

[63] Remark that a decrease in R&D investments of the incumbent and the entrants results in a later introduction time of the innovation. As society is often better off with an early introduction of the innovation, the social value P^* of the innovation could be reduced when the innovation is introduced later.

3.8. Conclusion

The study in this chapter contributes to the debate on leadership persistence or technological leapfrogging when there is competition for the market. The new and important result is that leadership persistence or technological leapfrogging does not only depend on exogenous versus endogenous entry but also on the assumption of winner-takes-all versus reward sharing. More specifically, it is shown that leadership persistence may also take place in markets with exogenous entry whereas technological leapfrogging can also occur in markets with free entry.

Indeed, when entry is assumed to be exogenous (the short run perspective), the study reveals that the incumbent invests in general less than the entrants. However, with reward sharing, this relationship may be reversed and leadership persistence is then more likely. This latter tendency prevails in patent races in which a winning incumbent takes it all but a winning entrant shares with the other entrants. Note that leadership persistence coincides here with monopoly persistence, as there is no reward sharing from the incumbent to the entrants.

Moreover, with endogenous entry, introducing reward sharing can alter the winner-takes-all tendency of leadership persistence. After all, when there is reward sharing from the incumbent to the entrants but not vice versa, the incumbent can be that much discouraged to invest by which leapfrogging might take place.

The findings here contribute to the existing literature. Etro (2007) states:

> *"We do not want to give the message that persistent monopolies are necessarily the fruit of effective competition [free entry] for the market, but rather that they can be the fruit of effective competition."*

The study in this chapter provides thus scenarios in which effective competition or free entry does not result in leadership persistence. Moreover, the study shows that leadership persistence can also occur in less competitive markets (exogenous entry). Thus, in addition to entry conditions, leadership persistence and technological leapfrogging moreover depend on how rewards of the innovation are shared. All in all, the incorporation of symmetric and asymmetric reward sharing can help the search for richer hypotheses to be tested in empirical work.

Furthermore, we have also shown that both the incumbent and the entrants overinvest in R&D compared to the social optimum. Moreover, with endogenous entry, too many firms participate in the race. This could clear the way for government intervention aiming at the reduction of excessive investments in R&D. Taxation of R&D investments could be one possible instrument. However, as the level of taxation depends then on several characteristics of the industry, such as the number of entrants and the degree of reward sharing, it may be clear that government's task tends to be rather complicated.

Finally, it would be interesting to analyze how R&D cartelization (maximization of joint profits) among entrants would change the results. After all, in chapter 2, it has been shown that R&D cartelization among followers could enhance technological leapfrogging. A second (obvious) extension would be to assume more than one incumbent and R&D cartelization among the incumbents. An interesting question would also be to evaluate whether R&D cooperation in patent races can reduce the excessive R&D investments of incumbents and entrants.

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Appendix

Calculation of $\frac{\partial(nh(z))}{\partial z^L}$ *with symmetric reward sharing S*

$$ZPC_S = \left[\left(1-\frac{1-\sigma}{n}\right)h(z)P + h\left(z^L\right)\left(\frac{1-\sigma}{n}\right)P - z\right] - F\left[r + nh(z) + h\left(z^L\right)\right] = 0$$

$$\frac{\partial n}{\partial z^L} = \left(-\frac{\partial ZPC/\partial z^L}{\partial ZPC/\partial n}\right) = \frac{h'\left(z^L\right)\left[\left(\frac{1-\sigma}{n}\right)P - F\right]}{h\left(z^L\right)\left(\frac{1-\sigma}{n^2}\right)P - h(z)\left(\frac{1-\sigma}{n^2}\right)P + Fh(z)}$$

$$\frac{\delta(nh(z))}{\delta z^L} = \frac{\partial n}{\partial z^L}h(z) + nh'(z)\frac{\partial z}{\partial z^L} = \left(-\frac{\partial ZPC_S/\partial z^L}{\partial ZPC_S/\partial n}\right)h(z) + 0 = \frac{h'\left(z^L\right)\left[\left(\frac{1-\sigma}{n}\right)P - F\right]}{\left(\frac{1-\sigma}{n^2}\right)\frac{h\left(z^L\right)}{h(z)} - \left(\frac{1-\sigma}{n^2}\right)P + F}$$

$$so \quad \left.\frac{\partial(nh(z))}{\partial z^L}\right|_{z^L=x} = \frac{h'(x)\left[\left(\frac{1-\sigma}{n}\right)P - F\right]}{\left(\frac{1-\sigma}{n^2}\right)\frac{h(x)}{h(z)} - \left(\frac{1-\sigma}{n^2}\right)P + F}$$

Calculation of $\frac{\partial(nh(z))}{\partial z^L}$ *with asymmetric reward sharing A1*

$$ZPC_{A1} = h(z)P + h\left(z^L\right)\left(\frac{1-\sigma}{n}\right)P - z - F\left[r + nh(z) + h\left(z^L\right)\right] = 0$$

$$\frac{\partial(nh(z))}{\partial z^L} = \frac{\partial n}{\partial z^L}h(z) + nh'(z)\times\frac{dz}{dz^L} = \left(-\frac{\partial ZPC/\partial z^L}{\partial ZPC/\partial n}\right)h(z) + 0 = \frac{h'\left(z^L\right)\left[\left(\frac{1-\sigma}{n}\right)P - F\right]}{\frac{h\left(z^L\right)}{h(z)}\left(\frac{1-\sigma}{n^2}\right)P + F}$$

$$so \quad \left.\frac{\partial(nh(z))}{\partial z^L}\right|_{z^L=x} = \frac{h'(x)\left[\left(\frac{1-\sigma}{n}\right)P - F\right]}{\frac{h(x)}{h(z)}\left(\frac{1-\sigma}{n^2}\right)P + F}$$

Calculation of $\frac{\partial(nh(z))}{\partial z^L}$*. with asymmetric reward sharing A2*

$$\frac{\partial\left(nh(z)\right)}{\partial z^L}=\frac{\partial n}{\partial z^L}h(z)+nh'(z)\frac{dz}{dz^L}=\left(-\frac{\partial ZPC/\partial z^L}{\partial ZPC/\partial n}\right)h(z)+0=h(z)\left(-\frac{-h'\left(z^L\right)F}{-h(z)F}\right)=-h'\left(z^L\right)$$

$$so\ \left.\frac{\partial\left(nh(z)\right)}{\partial z^L}\right|_{z^L=x}=-h'(x)$$

4. Cournot versus Bertrand competition with cost-reducing R&D and input spillovers

Joint work with Professor Jeroen Hinloopen

In this study, the economic performance of Cournot and Bertrand competition in a duopoly with substitutable goods is considered. Production costs are endogenous in the sense that, before competing in the product market, firms can invest in cost-reducing R&D, either in competition or in cooperation with each other. Economic performance between these two competition modes is compared in terms of R&D investments, profits, prices and total surplus. The study indicates that markets in which there is less competition intensity (Cournot markets) are better breeding grounds for R&D activity. Furthermore, it is shown that prices can be lower under Cournot competition than under Bertrand competition, both with R&D competition and R&D cooperation in the first stage. This occurs when the R&D process is efficient, when spillovers are substantial, and when products are not too differentiated. A key feature of the analysis is that technological spillovers are assumed to be an input of the R&D process rather than an output. As far as we know, this study is the first to report that with cost-reducing R&D and input spillovers, consumer surplus can be higher with Cournot competition than with Bertrand competition, both in case of R&D competition and R&D cooperation. So, this study contributes to a better understanding of the efficiency of Cournot and Bertrand competition. Moreover, the study points out that firms' R&D investments are always higher with Cournot than with Bertrand competition by which more insights in the relation between market structure and innovative activity are provided.

4.1. Introduction

When symmetric firms supply demand substitutes and market structure is exogenous, it is widely held that competition over price (Bertrand competition) yields lower prices and higher quantities than competition over quantities (Cournot competition)[64].

[64] When duopolists supply market complements, Bertrand competition still results in the lowest prices and highest static welfare, but firms' profits are higher with competition over prices than competition over quantities (Singh and Vives, 1984). Häckner (2000) shows, however, that Cournot competition

Accordingly, in the former profits are lower and consumer surplus is higher than in the latter. Moreover, the reduction in producer surplus with Bertrand competition is more than offset by the concomitant increase in consumer surplus, by which Bertrand markets turn out to be more efficient compared to Cournot markets. This renowned result was first established by Sing and Vives (1984) for a differentiated duopoly (a geometric approach of this result can be found in Cheng (1985)) and has been generalized by Vives (1985) for a differentiated oligopoly. When duopolistic firms are asymmetric (in terms of unit costs or demand), prices are still lower with Bertrand competition compared to Cournot competition but price competition can sometimes result in higher producer surplus compared to quantity competition, namely when firms are highly asymmetric and products are sufficiently differentiated. Consequently, total welfare, as the sum of consumer and producer surplus, is still always higher with Bertrand competition than with Cournot competition (Zanchettin, 2006).

Considering endogenous market structures may however reverse the traditional welfare comparison of Cournot and Bertrand competition. Cellini et al. (2004) and Mukherjee (2005) show that under free entry, total welfare can be higher with quantity competition than with price competition when the products are sufficiently differentiated. After all, the number of firms entering under Cournot competition exceeds the number under Bertrand competition. The resulting increase in the number of product varieties can more than compensate for the higher price that always obtains under Cournot competition when products have a low degree of substitutability.

Alternatively, market structure can also be endogenous in the sense that the competition in the product market is preceded by a stage where firms bargain on wages with labor unions (Lopez and Naylor, 2004) or conduct research and development (R&D) aimed at increasing product quality (Symeonidis, 2003) or lowering production costs (Qiu, 1997). With wage bargaining in the first stage, only the profit comparison can be reversed (Lopez and Naylor, 2004). After all, when labor unions are both relatively powerful and place sufficient weight on wages in their objective functions, profits are higher with price than with quantity competition. Yet,

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can yield lower prices than Bertrand competition when more than two firms market complements and quality differences are large.

consumer surplus and total welfare under Cournot competition always fall short of that under Bertrand competition.

When the product market stage is preceded by a stage of investments in product or process R&D, welfare can be higher under Cournot competition than under Bertrand competition as the incentives to invest in R&D are higher under the former than under the latter mode of competition (Qiu, 1997; Symeonidis, 2003)[65]. For process R&D post-innovative production costs under Cournot competition are then reduced more than under Bertrand competition. With a symmetric cost structure, profits are larger under Cournot competition than under Bertrand competition. This difference is then enhanced further if ex post production costs are lower under Cournot competition than under Bertrand competition. As a result, total welfare under Cournot competition can exceed total welfare under Bertrand competition (Qiu, 1997), despite the fact that the price under Bertrand competition is always lower than under Cournot competition. For product R&D similar results apply although here the higher welfare under Cournot competition is due to higher qualities which directly enhance consumer surplus (Symeonidis, 2003).

In this study, the celebrated result of Sing and Vives (1984) is qualified by showing that Cournot competition can yield lower prices than Bertrand competition in a duopoly, which supplies demand substitutes, with endogenous production costs. Production costs are endogenous in the sense that both firms invest in cost-reducing R&D before competing in the product market with differentiated products. Both the setting with R&D competition and R&D cooperation in the first stage are analyzed. Besides the possibility of lower prices with Cournot compared to Bertrand competition, the study also shows that R&D investments are always higher when firms compete with quantities, which is in line with Qiu (1997) and Symeonidis (2003).

[65] However, in some studies, the comparison of Cournot and Bertrand incentives is reversed. Firstly, when only one duopolist invests in cost-reducing R&D and there are no spillovers, Bester and Petrakis (1993) show that R&D incentives may be higher with Bertrand than with Cournot competition when the degree of product substitutability is sufficiently large. This result is due to the fact that, by investing heavily in cost-reducing R&D with Bertrand competition, the investing firm can force the non-investing firm out of the market. Secondly, if firms conduct both process and product R&D, the incentives comparison across competition types might change as well (Lin and Saggi, 2002).

A motivating example for the analysis in this chapter is the semiconductor industry. In this industry, competition with quantities is more relevant than competition with prices as capacities can not be expanded quickly due to capacity constraints. One of the characteristics of the semiconductor industry is the high R&D intensity of firms. For example, in 1989, the R&D intensity of firms in the semiconductor was more than 12% (Irwin and Klenow, 1996). Moreover, the industry has been characterized by very rapid price declines. In the 1990s, for instance, prices have been falling with more than 36% per year by which low prices prevail in the semiconductor industry. These decreases in prices can, to some extent, be attributed to technological innovations lowering the production costs[66] (Aizcorbe, 2002). This example suggests thus that low prices may prevail when firms compete with quantities[67].

Apparently, the analysis here is closely related to that of Qiu (1997), but two major differences should be stressed, i.e. the way in which spillovers are modelled and the allowance for R&D cooperation in the R&D stage.

In the study here, technological spillovers are considered to occur during the R&D process while Qiu (1997) assumes that final R&D results spill over. That is, input spillovers rather than output spillovers are considered. With output spillovers, it is assumed that part of the completed R&D project spills over to the rivals[68]. However, when input spillovers are considered, information leaks out to rivals before the completion of the R&D project, thus during the R&D process.

There are at least three important motivations for considering input spillovers instead of output spillovers. First, empirical studies indicate that spillovers indeed occur during the R&D process (Kaiser, 2002). This finding corresponds to the three channels that Geroski (1995) identifies through which a technological spillover can

[66] Other factors contribute to the price declines as well. For example, learning-by-doing has also been playing an important role in the falling prices in the semiconductor industry (Irwin and Klenow, 1994).
[67] The alternative pricing pattern when firms would compete with prices in the semiconductor industry is of course not available.
[68] Reverse engineering may serve as an example of a channel through which output spillovers can take place. For instance, at the end of the Second World War, when the first German V-1 flying bomb or cruise missile struck in England on June 12, 1944, American engineers started applying reverse engineering to the components of the V-1 bomb. This resulted in the first successful test flight of the JB-2, the American version of guided missiles, only a few months later (October 1944).
Source: Cummings in IEEE Technology and Society Magazine, Winter 2003/2004.

occur: (i) the exchange of ideas through publications, casual encounters and at seminars, (ii) the flow of knowledge when a knowledge worker changes employer, and (iii) the deduction of the line of reasoning of rivals by observing their behaviour. Thus, R&D from one firm to another mostly spills over during the R&D process, by which these spillovers are called input spillovers.

Second, Qiu (1997) assumes the R&D results of one firm to be perfectly additive to its rival's R&D results. However, there are at least three reasons to question this assumption. Note that the two firms operate in the same product market while initially using the same production technology. It is then most likely that there will be some overlap in their independently obtained research results that are aimed at reducing the costs of production. Also, the parts that do not overlap are expected not to be a perfect match to rival's research results. Finally, differences in corporate culture, research strategies, and internal organization hamper any firm's ability to fully appropriate rival's research results. In sum, high levels of technological output spillovers are not likely to be observed (Gerschbach and Schmutzler (2003) take an extreme position here by assuming that all of any firm's R&D results are perfectly additive to any of its rivals' R&D results).

Third, Qiu (1997) assumes diminishing returns to scale in R&D. In combination with additive output spillovers this has a counter-intuitive implication. If one firm has spent more on R&D than its rival, it could be in the interest of the former to donate its next R&D investment dollar to its rival and to appropriate the R&D results through the technological spillover. If these spillovers are substantial this could result in a more effective additional cost reduction than spending this last R&D dollar on own R&D (Amir, 2000).

Another important difference between this study and that of Qiu (1997) is that here, the efficiency of Cournot and Bertrand markets is not only analyzed for R&D competition but also for R&D cooperation in the investment stage[69]. After all, a well-known and important aspect of R&D is its public good character, which is reflected in the free flow of knowledge that is generated by any firm conducting R&D (the

[69] In this chapter, R&D cooperation is defined as the maximization of joint profits without increasing the knowledge spillover (cfr. R&D cartelization in chapter 2). .

technological spillover). According to Kamien et al. (1992) this technological spillover creates two externalities that influence firms' R&D investment decisions[70]. First there is the competitive advantage externality whereby any firm's R&D activities strengthen rivals' position in the product market through the reduction in rivals' production costs. This reduces the incentives to conduct R&D, by which this externality is always negative. Second, any firm's reduction in production costs adds to the joint profits. This combined-profits externality can be either positive or negative. The weaker the technological spillover is, the more likely it is that this externality is negative. Indeed, only in case the technological spillover is substantial, the rivals' research effort contributes to own profits through the concomitant cost reduction. Firms competing in R&D only consider the first externality when deciding how much to invest in R&D. R&D cooperatives also take the combined-profits externality into account. Consequently, it can be expected that comparing Bertrand and Cournot markets will yield different results dependent on R&D competition or R&D cooperation in the first stage.

For these reasons, the efficiency of Cournot and Bertrand competition is re-examined assuming input spillovers and R&D competition or R&D cooperation in the first stage. Moreover, firm's incentives under Cournot and Bertrand competition are compared. In passing, a technical error in Qiu (1997), related to the stability of equilibria when R&D is a strategic substitute, is revealed.

Note that the ambition of this study is not to compare the economic performance of R&D competition with R&D cooperation, as this has already been done before. When firms compete with quantities, R&D cooperation yields higher R&D investments, consumer and total surplus compared to R&D competition if, and only if, the spillover is larger than $\theta/2$ (with θ indicating the degree of product differentiation[71]). When firms compete with prices, the spillover also needs to exceed a certain threshold value in order R&D cooperation yields higher investments, consumer and total surplus. More specifically, this critical spillover is equal to $\theta/(2-\theta^2)$ (Hinloopen, 1997).

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[70] A more detailed description of these two externalities can be found in Hinloopen (1997).
[71] When $\theta=1$, products are homogeneous. When $\theta=0$, products are completely differentiated.

The main results of our study are the following. It is found that, both with R&D competition and cooperation, firms always invest more in cost-reducing R&D when they compete with quantities. Moreover, the study reports the important new message that prices can be lower under Cournot competition, namely when products are not that differentiated, when technological spillovers are strong, and when the R&D production process is sufficiently efficient. It is precisely under these circumstances that the incentives to conduct R&D are much larger under Cournot competition than under Bertrand competition as in this case much more of the benefits of any cost reduction are transferred to consumers when there is price competition. As a result, post innovation costs are much lower under Cournot competition, which translates into a lower equilibrium price. The range of cases for which total surplus under Cournot competition exceeds that under Bertrand competition is even larger, as profits under Bertrand competition are always below those under Cournot competition.

The remainder of this chapter is organized as follows. Section 4.2 presents the model. In section 4.3., R&D investments, profits and prices are compared between Cournot and Bertrand competition given R&D competition. In section 4.4., the same analysis is done for R&D cooperation. Section 4.5 concludes.

4.2. The model

A two-stage game is considered. In the first stage firms invest in cost-reducing R&D. In the second stage they compete with either prices or quantities. Market demand in indirect form is linear and is given by[72]:

$$p_i = a - \left(q_i + \theta q_j\right), \qquad (4.1)$$

i,j=1,2, $i \neq j$, where p_i and q_i are the respective price and quantity of product i, and where θ captures the extent to which products are differentiated; in case θ=1 products are homogeneous while θ=0 corresponds to completely differentiated products (i.e. both firms have a local monopoly). These polar cases are further ignored, that is, $\theta \in]0,1[$. Unless stated otherwise, i,j=1,2, $i \neq j$ holds throughout the rest of the paper. Market demand in direct form is then given by:

[72] This follows from a standard quadratic utility function, see Singh and Vives (1984).

$$q_i = \frac{1}{1-\theta^2}\Big[(1-\theta)a - \big(p_i - \theta p_j\big)\Big]. \tag{4.2}$$

The industry consists of two firms each producing one version of the differentiated product. *Ex ante* marginal costs of production, c, are exogenously determined and are the same for the two firms. It is assumed that both firms are active, that is, $c<a$. These ex ante production costs can be reduced by investing in process-innovating R&D. Note that if one firm conducts R&D, the rival firm can absorb part of this effort without having to pay for it[73]. Accordingly, if firm i invests x_i in R&D, its effective R&D investments X_i are given by:

$$X_i = x_i + \beta x_j. \tag{4.3}$$

In (4.3), $\beta \in [0,1]$ represents the technological spillover. From this equation, it is clear that, due to the spillover, part of the *inputs* of the rival firm j can be absorbed by firm i, therefore, the spillovers is called *input* spillover[74]. The reduction in the marginal cost brought about by these R&D investments is determined by an R&D production function f. This function is a mapping from effective R&D inputs to cost reductions. Following Kamien et al. (1992) diminishing returns to scale in R&D are assumed: $f'>0$, $f''<0$ and $f(0)=0$. In particular we set:

$$f(X_i) = \sqrt{\frac{X_i}{\gamma}}, \tag{4.4}$$

whereby $\gamma>0$ determines the efficiency of the R&D phase. The higher the value of γ is, the less efficient the R&D production function is, as a given amount of R&D inputs then results in a smaller reduction in unit costs. Note that in this setting the technological spillover is an input of the R&D process. Firm i's profits then equal

$$\Pi_i = \pi_i - x_i, \tag{4.5}$$

[73] It is understood that firms have to conduct at least some R&D themselves to share in the rival's R&D activities (for an early recognition of this point see Cohen and Levinthal, 1989). We abstain from modelling this absorptive capacity as it would make the analysis intractable (see Kamien and Zang, 2000).

[74] Note the difference with the model with output spillovers (see d'Aspremont and Jacquemin, 1988). In their model, the R&D investments by firm i equal $\frac{\tau}{2}(x_i)^2$. The resulting cost reduction (the R&D output) for firm i is equal to x_i. Moreover, part of the output of firm j, x_j, spills over to firm i, by which the total reduction in unit costs for firm i amounts to $x_i+\beta x_j$. Thus, clearly, in the model of d'Aspremont and Jacquemin, the spillover β transfers R&D outputs from firm j to firm i.

with $\pi_i = p_i q_i - (c - y_i) q_i$ and $y_i = \sqrt{(x_i + \beta x_j)/\gamma}$.

First, the scenario with R&D competition is solved and analyzed (section 4.3), followed by the R&D cooperation scenario (section 4.4).

4.3. R&D competition

Both the Cournot and Bertrand game are solved by backward induction. Moreover, regularity conditions need to be taken into account, which limit the admissible parameter space. Then, it is possible to compare R&D investments, profits, prices and total welfare under Bertrand and Cournot competition.

4.3.1. Market equilibria

4.3.1.1. Second-stage Bertrand competition

Maximizing (4.5) over price yields equilibrium prices conditional on effective R&D efforts[75]:

$$\hat{p}_i(X_i, X_j) - c = \frac{(a-c)(2+\theta)(1-\theta) - 2y_i - \theta y_j}{4-\theta^2}. \tag{4.6}$$

Inserting (4.6) into (4.5) and maximizing the resulting profits over R&D investments results in the following cost reduction[76, 77]:

$$\tilde{y}_B = \frac{(a-c)(2-\theta^2-\theta\beta)}{\gamma(1+\theta)(2-\theta)(4-\theta^2)-(2-\theta^2-\theta\beta)}, \tag{4.7}$$

and concomitant total output:

$$\tilde{Q}_B = \frac{2\gamma(a-c)(4-\theta^2)}{\gamma(1+\theta)(2-\theta)(4-\theta^2)-(2-\theta^2-\theta\beta)}. \tag{4.8}$$

Single-firm equilibrium profits then equal:

$$\tilde{\Pi}_B = \frac{\gamma(1+\theta)(1-\theta^2)(4-\theta^2)^2-(2-\theta^2-\theta\beta)^2}{\gamma(1+\beta)(4-\theta^2)^2}(\tilde{q}_B)^2, \tag{4.9}$$

where $\tilde{Q}_B = 2\tilde{q}_B$. Consumer surplus and total surplus are then respectively given by:

[75] A hat refers to a conditional equilibrium outcome.
[76] A tilde refers to an unconditional equilibrium expression; superscript B stands for second-stage Bertrand competition.
[77] The concomitant second-order and stability conditions are dealt with below.

$$\widetilde{CS}_B = (1+\theta)\left(\tilde{q}_B\right)^2 \tag{4.10}$$

and:

$$\widetilde{TS}_B = \frac{\gamma(1+\beta)(1+\theta)\left(4-\theta^2\right)^2(3-2\theta)-2\left(2-\theta^2-\theta\beta\right)^2}{\gamma(1+\beta)\left(4-\theta^2\right)^2}\left(\tilde{q}_B\right)^2. \tag{4.11}$$

4.3.1.2. Second-stage Cournot competition

Maximizing (4.5) over quantities gives us:

$$\hat{q}_i\left(X_i, X_j\right) = \frac{(a-c)(2-\theta\beta)}{\gamma(2+\theta)\left(4-\theta^2\right)-(2-\theta\beta)}. \tag{4.12}$$

Maximizing each firm's profits over R&D investments after inserting (4.12) into (4.5) yields as cost reduction and concomitant total output level[78]:

$$\tilde{y}_C = \frac{(a-c)(2-\theta\beta)}{\gamma(2+\theta)\left(4-\theta^2\right)-(2-\theta\beta)}, \tag{4.13}$$

and:

$$\tilde{Q}_C = \frac{2\gamma(a-c)\left(4-\theta^2\right)}{\gamma(2+\theta)\left(4-\theta^2\right)-(2-\theta\beta)}. \tag{4.14}$$

Single-firm profits are given by:

$$\tilde{\Pi}_C = \frac{\gamma(1+\beta)\left(4-\theta^2\right)^2-(2-\theta\beta)^2}{\gamma(1+\beta)\left(4-\theta^2\right)^2}\left(\tilde{q}_C\right)^2, \tag{4.15}$$

with $\tilde{Q}_C = 2\tilde{q}_C$. Consumer surplus and total welfare under second-stage Cournot competition then equal:

$$\widetilde{CS}_C = (1+\theta)\left(\tilde{q}_C\right)^2, \tag{4.16}$$

and:

$$\widetilde{TS}_C = \frac{\gamma(1+\beta)(3+\theta)\left(4-\theta^2\right)^2-2(2-\theta\beta)^2}{\gamma(1+\beta)\left(4-\theta^2\right)^2}\left(\tilde{q}_C\right)^2. \tag{4.17}$$

[78] Superscript C stands for second-stage Cournot competition.

4.3.2. Regularity conditions

The R&D stage gives rise to eight regularity conditions. In addition to the two second-order conditions, post-innovation costs have to be positive and the equilibrium has to be stable. The second-order conditions under Bertrand and Cournot competition require, respectively:

$$\gamma \geq \frac{\left(2-\theta^2-\theta\beta\right)^3}{\left(1-\theta^2\right)\left(4-\theta^2\right)^2\left(2-\theta^2-\theta\beta^2\right)}, \tag{R1}$$

and

$$\gamma \geq \frac{\left(2-\theta\beta\right)^3}{\left(4-\theta^2\right)^2\left(2-\theta\beta^2\right)}. \tag{R2}$$

Under Bertrand and Cournot competition positive post-innovation costs respectively imply:

$$\gamma \geq \frac{a\left(2-\theta^2-\theta\beta\right)}{c\left(2-\theta\right)\left(1+\theta\right)\left(4-\theta^2\right)}, \tag{R3}$$

and

$$\gamma \geq \frac{a\left(2-\theta\beta\right)}{c\left(2+\theta\right)\left(4-\theta^2\right)}. \tag{R4}$$

Finally, the Routh-Hurwitz stability condition is that:

$$\frac{\partial^2 \widehat{\Pi}_i\left(x_i,x_j\right)}{\partial x_i^2}\frac{\partial^2 \widehat{\Pi}_j\left(x_i,x_j\right)}{\partial x_j^2}-\frac{\partial^2 \widehat{\Pi}_i\left(x_i,x_j\right)}{\partial x_i \partial x_j}\frac{\partial^2 \widehat{\Pi}_j\left(x_i,x_j\right)}{\partial x_i \partial x_j}>0. \tag{4.18}$$

This condition depends on the strategic nature of the R&D process. Following Bulow et al. (1985), we label decision variable x a strategic substitute in case $\frac{\partial^2 \widehat{\Pi}_i\left(x_i,x_j\right)}{\partial x_i \partial x_j}<0$, and a strategic complement if $\frac{\partial^2 \widehat{\Pi}_i\left(x_i,x_j\right)}{\partial x_i \partial x_j}>0$.

Accordingly, in a symmetric equilibrium condition (4.18) boils down to (see Hinloopen, 2007):

$$\frac{\partial^2 \Pi_i \left(x_i, x_j\right)}{\partial x_i^2} < \frac{\partial^2 \Pi_i \left(x_i, x_j\right)}{\partial x_i \partial x_j}, \tag{4.19}$$

for strategic substitutes. For strategic complements it reads as:

$$\frac{\partial^2 \Pi_i \left(x_i, x_j\right)}{\partial x_i^2} < -\frac{\partial^2 \Pi_i \left(x_i, x_j\right)}{\partial x_i \partial x_j}. \tag{4.20}$$

Under Bertrand competition these two stability conditions respectively translate into:

$$\gamma \geq \frac{\left(2-\theta^2-\theta\beta\right)^2}{\left(4-\theta^2\right)\left(2+\theta\right)\left(1-\theta\right)\left(2-\theta^2+\theta\beta\right)}, \tag{R5}$$

and

$$\gamma \geq \frac{\left(2-\theta^2-\theta\beta\right)}{\left(4-\theta^2\right)\left(2-\theta\right)\left(1+\theta\right)}. \tag{R6}$$

In case of Cournot competition the two stability conditions are:

$$\gamma \geq \frac{\left(2-\theta\beta\right)^2}{\left(4-\theta^2\right)\left(2-\theta\right)\left(2+\theta\beta\right)}, \tag{R7}$$

and

$$\gamma \geq \frac{\left(2-\theta\beta\right)}{\left(4-\theta^2\right)\left(2+\theta\right)}. \tag{R8}$$

Five of these regularity conditions are redundant as the following Lemma shows.

Lemma 1. Five of the eight regularity conditions can be ignored as they are less binding than the three remaining regularity conditions. More specifically, the parameter space is bounded by regularity conditions R4, R5 and R7.

Proof. It is immediate that R4 dominates R3, that R5 dominates R6, and that R7 dominates R8. Also, R5 dominates R1 and R7 dominates R2.

Note that Qiu (1997) considers the stability conditions only in case of R&D being a strategic complement. In his model the stability conditions for R&D as a strategic substitute under Cournot and Bertrand competition are respectively given by (using the notation in Qiu, 1997):

$$v > \frac{2(2-\theta\gamma)(1-\theta)}{(2-\gamma)\left(4-\gamma^2\right)}, \tag{4.21}$$

and

$$v > \frac{2(1-\theta)\left(2-\theta\gamma-\gamma^2\right)}{(1-\gamma)(2+\gamma)\left(4-\gamma^2\right)}, \tag{4.22}$$

where $\theta\in[0,1]$ is the output spillover, where v is the measure of the efficiency of the R&D process, and where $\gamma\in[0,1]$ indicates the extent of product differentiation. The analysis of Qiu (1997) applies only to R&D that is a strategic complement as it is straightforward to show that conditions (4.21) and (4.22) are more binding than the stability conditions when R&D is a strategic complement.

4.3.3. Cournot versus Bertrand

4.3.3.1. R&D investments

Comparing R&D efforts of the different competition modes leads to the following Proposition:

Proposition 4.1. When firms compete in R&D, their R&D investments and concomitant cost reductions are always larger with Cournot compared to Bertrand competition.

Proof. $\tilde{y}_C > \tilde{y}_B \Leftrightarrow (1+\theta)(2-\theta)(2-\theta\beta) > (2+\theta)\left(2-\theta^2-\theta\beta\right)$, or $\beta > -1$.

Moreover, $\tilde{y}_C > \tilde{y}_B \Leftrightarrow \tilde{x}_C > \tilde{x}_B$.

According to Proposition 4.1, R&D activity is higher under Cournot competition than under Bertrand competition. This result is not that surprising and replicates Qiu (1997) who points out that there are four effects at work when firms decide upon their R&D investments, i.e. a cost effect, a size effect, a spillover effect and a strategic effect. Analyzing the sign of these effects contributes to the understanding and the intuition of this result. A detailed analytical derivation of these signs is presented in the appendix of this chapter.

With Cournot competition, this decomposition yields:

$$\frac{\partial \Pi_i}{\partial x_i} = \underbrace{\left[\frac{y_j}{2\gamma y_i y_j \Psi^C} \frac{\partial \pi_i}{\partial q_j} \frac{\partial^2 \pi_j}{\partial q_i \partial q_j}\right]}_{\text{strategic effect (+)}} + \underbrace{\left[\frac{-\beta y_i}{2\gamma y_i y_j \Psi^C} \frac{\partial \pi_i}{\partial q_j} \frac{\partial^2 \pi_i}{\partial q_i^2}\right]}_{\text{spillover effect (-)}} + \underbrace{\left[\frac{q_i}{2\gamma y_i}\right]}_{\text{size effect (+)}} + \underbrace{[-1]}_{\text{cost effect (-)}} .$$

And with Bertrand competition:

$$\frac{\partial \Pi_i}{\partial x_i} = \underbrace{\left[\frac{y_j}{2\gamma y_i y_j \Psi^B} \frac{\partial \pi_i}{\partial p_j} \frac{\partial^2 \pi_j}{\partial p_i \partial p_j} \frac{\partial q_i}{\partial p_i}\right]}_{\text{strategic effect (-)}} + \underbrace{\left[\frac{-\beta y_i}{2\gamma y_i y_j \Psi^B} \frac{\partial \pi_i}{\partial p_j} \frac{\partial^2 \pi_i}{\partial p_i^2} \frac{\partial q_j}{\partial p_j}\right]}_{\text{spillover effect (-)}} + \underbrace{\left[\frac{q_i}{2\gamma y_i}\right]}_{\text{size effect (+)}} + \underbrace{[-1]}_{\text{cost effect (-)}} .$$

For both Bertrand and Cournot competition, the signs of the cost, size and spillover effect are the same. Firstly, the cost effect is negative as R&D is costly, resulting in disincentives for firms to invest in R&D. Secondly, the more a firm produces, the more this firm is willing to invest in R&D by which the size effect is thus positive. After all, the higher the output is, the larger the gain from a cost-reduction is. Thirdly, the spillover effect is negative as, due to the knowledge spillover, the rival firm can, to some extent, free ride on the efforts of the other firm, thereby reducing the R&D incentives of the latter.

But, fourthly, the sign of the strategic effect is different between quantity and price competition. In Cournot markets this strategic effect is positive. After all, by investing in R&D, firm *i* lowers its production costs and the firm with the lower production costs is the tougher competitor who has the largest market share and realizes the highest profits. Using the terminology of Fudenberg and Tirole (1984), the investing firm *i* pursues a top dog strategy[79] as it has an incentive to increase its R&D investments because these higher investments result in higher profits at the expense of its rival.

[79] See Fudenberg and Tirole (1984). A firm is called a top dog when its commitment is tough and the stage two variables are strategic substitutes. Indeed, an investment in cost-reducing R&D by firm *i* results in a higher output of firm *i* (tough investment) and quantities are strategic substitutes in Cournot markets.

In Bertrand markets this strategic effect is negative as any reduction in production costs and its resulting decrease in price by firm *i* induce its rival *j* to cut its price as well. Consequently, in order to avoid such aggressive moves, the investing firm may be better off by reducing its R&D investments, which is typical for a puppy dog[80].

Consequently, firms are more willing to invest in R&D when there is Cournot competition. The switch from output spillovers to input spillovers does not affect this reasoning. The ranking in Proposition 4.1 is also found by Breton et al. (2004) who replicate the analysis of Qiu (1997) within an infinite horizon setting.

The actual difference in R&D activity that leads to the ranking in Proposition 4.1 is closely related to the efficiency of the R&D process. That is:

Lemma 4.2. With R&D competition, the difference in R&D activity between Cournot and Bertrand competition is larger the more efficient the R&D process is.

Proof. Note that

$$\tilde{y}_C - \tilde{y}_B = \frac{\gamma\theta^3\left(4-\theta^2\right)(1+\beta)(a-c)}{\left[\gamma(2+\theta)\left(4-\theta^2\right)-(2-\theta\beta)\right]\left[\gamma(1+\theta)(2-\theta)\left(4-\theta^2\right)-\left(2-\theta^2-\theta\beta\right)\right]}.$$

Then, observe that $\frac{\partial\left(\tilde{y}_C - \tilde{y}_B\right)}{\partial\gamma} > 0 \Leftrightarrow \gamma^2 > \frac{(2-\theta\beta)\left(2-\theta^2-\theta\beta\right)}{(1+\theta)\left(4-\theta^2\right)^3}$. This last condition is less binding than R7 if, and only if, $(2-\theta\beta)^3(1+\theta)\left(4-\theta^2\right)-\left(2-\theta^2-\theta\beta\right)(2-\theta)^2(2+\theta\beta)^2 > 0$. Considering the left-hand side (LHS) of this last inequality, the result then follows as $\min_{\{\theta,\beta\}} LHS = \lim_{\theta\to 0} LHS\big|_{\beta=1} = 0$.

The larger the reduction in production costs for any level of R&D investments is, the more prominent the strategic effect is that affects any firm's incentive to conduct

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[80] See Fudenberg and Tirole (1984). A firm is called a puppy dog when its commitment is tough and the stage two variables are strategic complements. Indeed, the investment of firm *i* is tough as an investment in R&D results in a lower price of firm *i* and prices are strategic complements in Bertrand markets.

R&D. Hence, the more efficient the R&D process is (thus the lower the value for γ is), the larger the difference in R&D investments is under Cournot competition vis-à-vis Bertrand competition.

Note that the difference between investments under Cournot and Bertrand competition is also larger the less differentiated the products are. Indeed, the reward in terms of market share for an investing firm with Cournot competition is larger the less differentiated products are whereas with Bertrand competition the price cut by one firm as a response to a price decrease by its rival tends to be larger the less differentiated products are. Consequently, the more substitutable products are, the larger the wedge between Cournot and Bertrand investment incentives is.

Moreover, the difference between investments under Cournot and Bertrand competition is increasing in the spillover. After all, the more intense market competition is, the more firms are discouraged by larger free riding opportunities by rivals. Consequently, an increase in the spillover discourages Bertrand firms more than Cournot firms as Bertrand competition is more intense than Cournot competition. These two comparative statics were also found by Symeonidis (2003).

4.3.3.2. Profits

Under Cournot competition firms invest more in R&D than under Bertrand competition (Proposition 4.1). And larger R&D investments reduce profits, all else equal. However, under Cournot competition, the resulting reductions in unit costs more than compensate for these higher R&D investments, by which profits are always higher with Cournot competition than with Bertrand competition. This result generalizes the traditional ranking of profits (and thus producer surplus) under both modes of competition, as was found by Singh and Vives (1984). The following Proposition summarizes this finding. Consequently, firms are always both better off when they compete with quantities compared to prices.

Proposition 4.2. With R&D competition, firms' profits are always higher with Cournot than with Bertrand competition.

Proof. First note that $\widetilde{\Pi}_C - \widetilde{\Pi}_B = \gamma(a-c)^2 (A-B)/(1+\beta)$, where

$$A = \frac{\gamma(1+\beta)(4-\theta^2)^2 - (2-\theta\beta)^2}{\left[\gamma(2+\theta)(4-\theta^2) - (2-\theta\beta)\right]^2},$$

and

$$B = \frac{\gamma(1+\beta)(1-\theta^2)(4-\theta^2)^2 - (2-\theta^2-\theta\beta)^2}{\left[\gamma(1+\theta)(2-\theta)(4-\theta^2) - (2-\theta^2-\theta\beta)\right]^2}.$$

Then observe that:

$$\widetilde{\Pi}_C - \widetilde{\Pi}_B > 0 \Leftrightarrow \gamma > \frac{2(4-3\theta^2) - \theta(1-\beta)(\theta^2-2\theta-4)}{2(1+\theta)(4-\theta^2)^2}.$$

This last condition is less binding than condition R7 if, and only if, $(1-\beta)\left[32+16\theta-12\theta^2-16\theta\beta-2\theta^3(1+\beta)+8\theta^3\beta\right]+\theta^2\beta\left[8\beta-\theta^2(1+\beta)\right]>0$. Considering the LHS of this last inequality the result then follows as $\min_{\{\theta,\beta\}} LHS = \lim_{\theta\to 0} LHS\big|_{\beta=1} = 0$.

Consequently, it could be in the interest of both firms to compete with quantities. However, the competition modes in industries are often determined by the underlying technology. Indeed, firms tend to compete with quantities in industries characterized by capacity constraints (for example the automobile industry) whereas Bertrand competition is more relevant in industries in which there are no constraints on capacity. Consider for example the market for downloadable music. In this market, it is hard, not to say impossible, for firms to credibly commit to a certain capacity as it is impossible to limit the number of downloads of songs. After all, capacity can be expanded very quickly, by which firms will soon end up in Bertrand competition.

To continue, as post-innovation production costs are lower under Cournot competition, this larger producer surplus can compensate for the lower consumer surplus in Cournot markets compared to Bertrand markets by which total welfare might be higher with quantity competition than with price competition. But before total surplus is analyzed, consumer surplus is considered first.

4.3.3.3. Price

For comparing prices under Cournot and Bertrand competition, the following assumption is introduced:

$$\gamma < \frac{1}{4-\theta^2} \qquad \text{(A1)}$$

If assumption A1 holds, the R&D process is labeled 'efficient' as a small value for γ corresponds to a relatively large reduction in unit costs for a given amount of R&D inputs (see section 4.2). According to Lemma 4.2, This corresponds to situations where post-innovation costs under Cournot competition are particularly low compared to post-innovation costs under Bertrand competition, as it is known that the difference in R&D investments and concomitant cost reductions are larger the more efficient the R&D process is (see Lemma 4.2). As will be shown below, this difference in ex post unit costs can be that large that the equilibrium price can be lower under Cournot competition than under Bertrand competition. First note that the assumption A1 of an efficient R&D process does not rule out the existence of equilibria:

Lemma 4.3. The set where regularity conditions R4, R5, R7 and assumption A1 hold is not empty.

Proof. For A1 and R4 to hold jointly it is required that $1 < a/c < (2+\theta)/(2-\theta\beta)$, or $2(a-c) < \theta(a\beta + c)$. Indeed, a and c can always be chosen such that this inequality holds. For A1 and R5 to hold jointly it is required that $1 > \left(2-\theta^2-\theta\beta\right)^2 / \left[(2+\theta)(1-\theta)\left(2-\theta^2+\theta\beta\right)\right]$ or $\beta > \left(6-3\theta^2-\theta-\sqrt{(1-\theta)\left(36+16\theta-19\theta^2-9\theta^3\right)}\right)/2\theta = f(\theta)$. Note that $f(\theta)$ is continuous and strictly increasing in $\theta \in]0,1[$, that $\lim_{\theta\to 0} f(\theta) = \frac{1}{3}$, and that $\lim_{\theta\to 1} f(\theta) = 1$. For A1 and R7 to hold jointly it is required that $1 > (2-\theta\beta)^2 / \left[(2-\theta)(2+\theta\beta)\right]$ or $\beta > \left(6-\theta-\sqrt{(18-\theta)(2-\theta)}\right)/2\theta = \mathrm{g}(\theta)$. Note that $g(\theta)$ is continuous and strictly increasing in $\theta\in]0,1[$, that $\lim_{\theta\to 0} g(\theta)=\frac{1}{3}$, and that $\lim_{\theta\to 1} g(\theta)=\left(5-\sqrt{17}\right)\approx 0.438$.

Figure 4.1 displays the admissible parameter space and assumption A1 for particular values of a, c, and γ. Note that from the proof of Lemma 4.3 it follows that $f(\theta)$-$g(\theta)$>0, $\forall\ \theta\in]0,1[$. Hence, under assumption A1 the admissible parameter space is confined by regularity conditions R4 and R5. It is now possible to state the main result of the analysis:

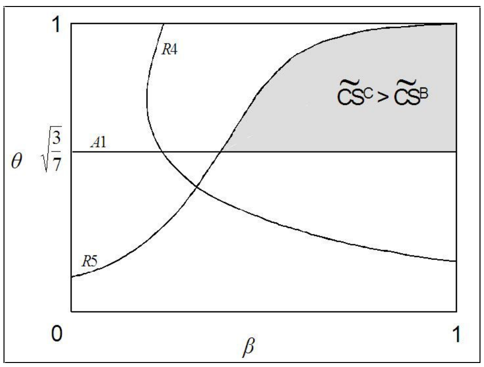

Figure 4.1. Comparing consumer surplus with Cournot and Bertrand competition under assumption A1 and regularity conditions R4 and R5 (a=100, c=70, γ=7/25) with R&D competition.

Proposition 4.3. With R&D competition, prices are lower under Cournot competition than under Bertrand competition when the R&D process is efficient, spillovers are high and products are not that differentiated.

Proof. Lower prices obtain under Cournot competition than under Bertrand competition if, and only if, $\tilde{Q}_C > \tilde{Q}_B$, or $\gamma < 1/(4-\theta^2)$.

Proposition 4.3 conveys the new message of this study. In a duopoly with substitutable products, total quantities produced can be higher under Cournot competition than under Bertrand competition. Or, in other words, prices can be lower when firms compete with quantities than when they compete with prices. This happens when post-innovation costs under Cournot competition are sufficiently below post-innovation costs under Bertrand competition. Considering the admissible parameter space in Lemma 4.3, this occurs when the R&D process is efficient, spillovers are substantial, and products are not that differentiated. It is precisely under these circumstances that the benefits of any cost reduction are transferred to a much larger extent to consumers under Bertrand competition than under Cournot competition or, in other words, it is precisely then that the strategic effect is most prominent. Consequently, the difference between R&D investments between Cournot and Bertrand competition is then that large by which production costs under Cournot competition are much lower than under Bertrand competition. Due to this large difference in ex post unit costs, it is possible that the equilibrium price is lower with Cournot than with Bertrand competition.

When prices are lower with Cournot than with Bertrand competition, the reverse is true for consumer surplus. Consumers can thus be better off with Cournot competition than with Bertrand competition when the spillovers are high, products are not that differentiated and the R&D process is efficient. Less intense competition modes, such as Cournot competition, may thus sometimes result in higher consumer surplus, compared to more intense competition modes, such as Bertrand competition.

4.3.3.4. Welfare

As producer surplus is always higher under Cournot competition than under Bertrand competition (Proposition 4.2), the result in Proposition 4.3 carries over to total surplus as both consumer and producer surplus are then higher with competition over quantities than with competition over prices:

Proposition 4.4. With R&D competition, total surplus is higher under Cournot competition than under Bertrand competition when the R&D process is efficient, spillovers are high and products are not that differentiated.

However, for a less efficient R&D production process ($\gamma > \frac{1}{4-\theta^2}$), it is still possible that total surplus under Cournot competition exceeds total surplus under Bertrand competition. In that case, consumer surplus is lower when firms compete over quantities (Proposition 4.3). But this lower consumer surplus is then more than compensated for by the higher producer surplus under Cournot competition, provided strict positive technological spillovers. After all, when there are no spillovers, total surplus is always higher with Cournot competition compared to Bertrand competition, as is formalized in Proposition 4.5.

Proposition 4.5. With R&D competition, total surplus is always higher with Bertrand competition than with Cournot competition, provided that there are no spillovers (β=0) and that the R&D process is not that efficient.

Proof. See Appendix.

When input spillovers are absent, the traditional welfare comparison emerges in case the R&D production process is not too efficient ($\gamma > \frac{1}{4-\theta^2}$). However, for positive input spillovers the difference in R&D investment incentives under Cournot and Bertrand competition becomes more pronounced. Indeed, a threshold value of the input spillover exists beyond which total surplus is larger if firms compete over quantity rather than over price:

Proposition 4.6. When firms compete in R&D and the R&D process is not that efficient ($\gamma > \frac{1}{4-\theta^2}$), total surplus can be higher under Cournot than under Bertrand competition when the spillover is sufficiently high and the R&D process is still sufficiently efficient.

Proof. See Appendix.

Technological spillovers carry a positive externality that raises total surplus. The combination of large R&D investments and strong technological spillovers contributes in particular to total surplus. Hence, as under Cournot competition R&D investments exceed those under Bertrand competition, total surplus can be larger under quantity competition when the input spillover is strong enough, provided that the R&D process is not that efficient (as in A1), but still efficient enough. When the R&D process is rather inefficient, total surplus is always higher under Cournot competition.

4.4. R&D cooperation

In this section, it is analyzed whether the observed tendencies with R&D competition still apply when firms are allowed to cooperate in R&D before competing on the market. R&D cooperation is here defined as the coordination of strategies, without increasing the spillovers[81]. Again, both the Bertrand and Cournot game are solved by backward induction. Regularity conditions determine the admissible parameter space in which the performance of Cournot and Bertrand markets needs to be compared. Note that it is assumed that R&D cooperation never leads to collusion on the output market, although some studies show that cooperation in R&D makes it more likely that firms collude on the product market (Martin, 1995; Suetens, 2008).

4.4.1. Market equilibria

4.4.1.1. Second-stage Bertrand competition

Maximizing (4.5) over price yields equilibrium prices conditional on effective R&D efforts[82]:

$$\widehat{p}_i\left(X_i, X_j\right) - c = \frac{(a-c)(2+\theta)(1-\theta) - 2y_i - \theta y_j}{4-\theta^2}. \tag{4.23}$$

Inserting (4.23) into (4.5) and maximizing the resulting sum of firms' profits over R&D investments results in the following cost reduction[83, 84]:

$$\tilde{y}_B = \frac{(a-c)(2+\theta)^2 (1\text{-}\theta)^2 (1+\beta)}{\gamma\left(4-\theta^2\right)^2\left(1-\theta^2\right) - (2+\theta)^2 (1-\theta)^2 (1+\beta)}, \tag{4.24}$$

and concomitant total output:

$$\widetilde{Q}_B = \frac{2\gamma(a-c)(2+\theta)(1-\theta)\left(4-\theta^2\right)}{\gamma\left(4-\theta^2\right)^2\left(1-\theta^2\right) - (2+\theta)^2(1-\theta)^2(1+\beta)}. \tag{4.25}$$

Single-firm equilibrium profits then equal:

$$\widetilde{\Pi}_B = \frac{\gamma\left(1-\theta^2\right)\left(4-\theta^2\right)^2 - (2+\theta)^2(1-\theta)^2(1+\beta)}{\gamma\left(4-\theta^2\right)^2}\left(\tilde{q}_B\right)^2, \tag{4.26}$$

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[81] In the terminology of chapter 2, firms form an R&D cartel.

[82] A hat refers to a conditional equilibrium outcome.

[83] A tilde refers to an unconditional equilibrium expression; superscript B stands for second-stage Bertrand competition.

[84] The concomitant second-order conditions are dealt with below.

where $\widetilde{Q}_B = 2\tilde{q}_B$. Consumer surplus and total surplus are then respectively given by:

$$\widetilde{CS}_B = (1+\theta)\left(\tilde{q}_B\right)^2, \tag{4.27}$$

and:

$$\widetilde{TS}_B = \frac{\gamma\left(4-\theta^2\right)^2(1+\theta)(3-2\theta)-2(2+\theta)^2(1-\theta)^2(1+\beta)}{\gamma\left(4-\theta^2\right)^2}\left(\tilde{q}_B\right)^2. \tag{4.28}$$

4.4.1.2. Second-stage Cournot competition

Maximizing (4.5) over quantities gives us:

$$\hat{q}_i\left(X_i, X_j\right) = \frac{(a-c)(2-\theta)+2y_i-y_j}{4-\theta^2}. \tag{4.29}$$

Maximizing the sum of both firms' profits over R&D investments after inserting (4.29) into (4.5) yields as cost reduction and concomitant total output level[85]:

$$\tilde{y}_C \frac{(a-c)(2-\theta)^2(1+\beta)}{\gamma\left(4-\theta^2\right)^2-(2-\theta)^2(1+\beta)}, \tag{4.30}$$

and:

$$\widetilde{Q}_C \frac{2\gamma(a-c)\left(4-\theta^2\right)(1+\beta)}{\gamma\left(4-\theta^2\right)^2-(2-\theta)^2(1+\beta)} \tag{4.31}$$

Single-firm profits are given by:

$$\widetilde{\Pi}_C = \frac{\gamma\left(4-\theta^2\right)^2-(1+\beta)(2-\theta)^2}{\gamma\left(4-\theta^2\right)^2}\left(\tilde{q}_C\right)^2, \tag{4.32}$$

with $\widetilde{Q}_C = 2\tilde{q}_C$. Consumer surplus and total welfare under second-stage Cournot competition then equal:

$$\widetilde{CS}_C = (1+\theta)\left(\tilde{q}_C\right)^2, \tag{4.33}$$

and:

$$\widetilde{TS}_C = \frac{\gamma\left(4-\theta^2\right)^2(3+\theta)-2(1+\beta)(2-\theta)^2}{\gamma\left(4-\theta^2\right)^2}. \tag{4.34}$$

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[85] Superscript C stands for second-stage Cournot competition.

4.4.2. Regularity conditions

The R&D stage gives rise to four regularity conditions. In addition to the two second-order conditions, post-innovation costs have to be positive. The second-order conditions under Bertrand and Cournot competition are, respectively:

$$\gamma \geq \frac{(1+\beta)\left[\left(2-\theta^2-\theta\beta\right)^2+\left(2\beta-\theta^2\beta-\theta\right)^2\right]}{\left(4-\theta^2\right)^2\left(1-\theta^2\right)\left(1+\beta^2\right)}, \tag{RR1}$$

and:

$$\gamma \geq \frac{(1+\beta)\left[(2-\theta\beta)^2+(2\beta-\theta)^2\right]}{\left(4-\theta^2\right)^2\left(1+\beta^2\right)}. \tag{RR2}$$

Under Bertrand and Cournot competition positive post-innovation costs respectively imply:

$$\gamma \geq \frac{a(1-\theta)(1+\beta)}{c(1+\theta)(2-\theta)^2}, \tag{RR3}$$

and:

$$\gamma \geq \frac{a(1+\beta)}{c(2+\theta)^2}. \tag{RR4}$$

One of these regularity conditions RR3 is redundant as is shown by the following Lemma.

Lemma 4.4. One of the four regularity conditions can be ignored as this condition is less binding than the three remaining regularity conditions. More specifically, the parameter space is bounded by regularity conditions RR1, RR2 and RR4.

Proof. It is immediate that RR4 dominates RR3.

4.4.3. Cournot versus Bertrand

4.4.3.1. R&D investments

Comparing the effective R&D efforts of the different competition modes leads to the following Proposition.

Proposition 4.7. When firms cooperate in R&D, their R&D investments and concomitant cost reductions are always larger with Cournot competition than with Bertrand competition.

Proof. $\tilde{y}_C > \tilde{y}_B \Leftrightarrow 2\gamma(a-c)(1+\beta)(4-\theta^2)^2(1-\theta)\theta^3 > 0$, or $\beta > -1$.

Moreover, $\tilde{y}_C > \tilde{y}_B \Leftrightarrow \tilde{x}_C > \tilde{x}_B$.

According to Proposition 4.7, R&D activity is higher under Cournot competition than under Bertrand competition when firms invest cooperatively in cost-reducing R&D prior to competing on the market. This result replicates the findings with R&D competition in the first stage, both for output (Qiu, 1997) and input spillovers (Proposition 4.1), by which the ranking of R&D activity under Cournot and Bertrand competition turns out to be robust for the introduction of R&D cooperation. Decomposing the total R&D effect in a strategic, a spillover, a size and a cost effect can again help to explain this tendency.

For Cournot competition, this decomposition of the R&D effect on total profits yields the following expression (with $\Pi_T=\pi_i+\pi_j$):

$$\frac{\partial \Pi_T}{\partial x_i} = \overbrace{\left[\frac{y_j}{2\gamma y_i y_j \Psi^C}\left(\overbrace{\left[\frac{\partial \pi_i}{\partial q_j}\frac{\partial^2 \pi_j}{\partial q_i \partial q_j}\right]}^{+} + \overbrace{\left[-\frac{\partial \pi_j}{\partial q_i}\frac{\partial^2 \pi_j}{\partial q_j^2}\right]}^{-}\right)\right]}^{\text{strategic effect (-)}}$$
$$+ \underbrace{\left[\frac{\beta y_i}{2\gamma y_i y_j \Psi^C}\left(\underbrace{\left[\frac{\partial \pi_j}{\partial q_i}\frac{\partial^2 \pi_i}{\partial q_i \partial q_j}\right]}_{+} + \underbrace{\left[-\frac{\partial \pi_i}{\partial q_j}\frac{\partial^2 \pi_i}{\partial q_i^2}\right]}_{-}\right)\right]}_{\text{spillover effect (-)}} + \underbrace{\left[\frac{q_i}{2\gamma y_i} + \frac{\beta q_j}{2\gamma y_j}\right]}_{\text{size effect (+)}} + \underbrace{[-1]}_{\substack{\text{cost}\\\text{effect}\\\text{(-)}}}.$$

And for Bertrand competition:

$$\frac{\partial \Pi_T}{\partial x_i} = \overbrace{\left[\frac{y_j}{2\gamma y_i y_j \Psi^B} \left(\overbrace{\left[\frac{\partial q_i}{\partial p_i} \frac{\partial^2 \pi_j}{\partial p_i \partial p_j} \frac{\partial \pi_i}{\partial p_j} \right]}^{-} + \overbrace{\left[-\frac{\partial q_i}{\partial p_i} \frac{\partial \pi_j}{\partial p_i} \frac{\partial^2 \pi_j}{\partial p_j^2} \right]}^{-} \right) \right]}^{\text{strategic effect (-)}}$$

$$+ \underbrace{\left[\frac{\beta y_i}{2\gamma y_i y_j \Psi^B} \left(\underbrace{\left[\frac{\partial q_j}{\partial p_j} \frac{\partial \pi_j}{\partial p_i} \frac{\partial^2 \pi_i}{\partial p_i \partial p_j} \right]}_{-} + \underbrace{\left[-\frac{\partial q_j}{\partial p_j} \frac{\partial \pi_i}{\partial p_j} \frac{\partial^2 \pi_i}{\partial p_i^2} \right]}_{-} \right) \right]}_{\text{spillover effect (-)}} + \underbrace{\left[\frac{q_i}{2\gamma y_i} + \frac{\beta q_j}{2\gamma y_j} \right]}_{\text{size effect (+)}} + \underbrace{[-1]}_{\substack{\text{cost} \\ \text{effect} \\ \text{(-)}}} .$$

So, apparently, when firms cooperate in R&D, not only the sign of the spillover, size and cost effects are the same under Cournot and Bertrand competition, but now the sign of the strategic effect is also the same. However, with R&D cooperation, the strategic and spillover effects each consist of two terms and analyzing the sign of these two terms explains why firms invest more in R&D under Cournot than under Bertrand competition. Note first that, for both Cournot and Bertrand competition, the cost effect is negative and the size effect is positive. Furthermore, note that, due to the cooperation in R&D, the impact on rival's output is also taken into account by the investing firm. Thus, the investing firm does not only take into account the impact of its R&D investments on its own profits, but also the impact on the profits of its rival. This is reminiscent of the internalization of the combined profits externality.

Contrary to R&D competition, the strategic effect with Cournot competition is now negative, as the negative second term dominates the positive first term. The first term of the strategic effect represents the positive effect of an investment by firm *i* on its own profits. After all, just like with R&D competition, an investment in cost-reducing R&D rewards firm *i* with a larger market share and hence higher profits. As a result, the investing firm has an incentive to increase its R&D investments. However, due to the increase in output of firm *i*, the profits of its rival are negatively affected by investments in R&D, which is now taken into account by the investing firm, due to the coordination of R&D strategies. This negative effect on R&D investments is represented by the second term of the strategic effect.

With Bertrand competition, the strategic effect is negative as its two constructing parts are negative. After all, an increase in the R&D investments of firm *i* incites both firms *i* and *j* to cut down their prices, by which both firms' profits are reduced. The negative effect on the own profits of the investing firm *i* reduces its incentives to invest in R&D and is represented by the first term of the strategic effect. Moreover, incentives are further discouraged by the negative effect on profits of the rival, which is represented by the second term of the strategic effect.

With Cournot competition, the spillover effect is also negative. Just like with R&D competition, part of firm *i*'s R&D spills over to its rival firm *j*, by which the latter's production efficiency is raised and, hence, output increases. This increase in output of firm *j* has a negative impact on the profits of the investing firm *i* but a positive effect on firm *j*'s profits. The former effect is represented by the second term of the spillover effect and is thus negative while the latter effect is positive and captured by the first term of the spillover effect. In total, the spillover effect is negative.

When there is Bertrand competition, the spillover effect is negative as well. Firm *i* is again discouraged to invest in R&D as a rival can free ride on the investing firm's R&D efforts. Due to this free riding, the rival firm *j* lowers its price, by which firm *i* reduces its price as well. Consequently, the spillover effect is negative as an increase in the investments of firm *i* reduces both firm *i*'s profits (second term of spillover effect) and firm *j*'s profits (first term of spillover effect).

Thus, the higher R&D activity with Cournot competition is due to the positive sign of first term of the strategic effect and the first term of the spillover effect. In short, this difference in R&D investments is a result of the fact that Cournot competition is less intense compared to Bertrand competition. After all, quantities are strategic substitutes in Cournot markets and prices are strategic complements in Bertrand markets. Consequently, an aggressive move by one firm incites a less aggressive move by its rival in Cournot markets but the rival will behave aggressively as well when firms compete with prices. Thus, R&D investments are more profitable in Cournot markets than in Bertrand markets. In other words, with Bertrand competition, cost-reductions are transferred much more to consumers than with Cournot competition.

To continue, the actual difference in R&D activity that leads to the ranking in Proposition 4.7 is closely related to the efficiency of the R&D process. That is:

Lemma 4.5. With R&D cooperation, the difference in R&D activity between Cournot and Bertrand competition is larger, the more efficient the R&D process is.

Proof. First note that

$$\tilde{y}_C - \tilde{y}_B = \frac{2\gamma(a-c)(1+\beta)\left(4-\theta^2\right)^2(1-\theta)\theta^3}{\left[\gamma\left(4-\theta^2\right)^2\left(1-\theta^2\right)-(2+\theta)^2(1-\theta)^2(1+\beta)\right]\left[\gamma\left(4-\theta^2\right)-(2-\theta)^2(1+\beta)\right]}.$$

Then observe that:

$$\frac{\partial\left(\tilde{y}_C-\tilde{y}_B\right)}{\partial\gamma}>0 \Leftrightarrow \gamma^2 > \frac{(1+\beta)^2(1-\theta)}{(1+\theta)\left(4-\theta^2\right)^2}.$$

This last condition is less binding than condition RR4 as $\left(\gamma^{RR4}\right)^2-\frac{(1+\beta)^2(1-\theta)}{(1+\theta)\left(4-\theta^2\right)^2}=\frac{2\theta^3(1+\beta)^2}{(1+\theta)\left(4-\theta^2\right)^2(2+\theta)^2}>0$, with $\gamma^{RR4}=\lim_{c\to a}\frac{a(1+\beta)}{c(2+\theta)^2}$.

A larger R&D efficiency may thus increase the wedge between Cournot and Bertrand incentives. Note furthermore that, just like with R&D competition, the difference between Cournot and Bertrand investment incentives increases when products become more substitutable and when spillovers are larger.

4.4.3.2. Profits

From Proposition 4.7, it is known that firms invest more in cost-reducing R&D in Cournot than in Bertrand markets. All else equal, these larger R&D investments would yield lower profits with Cournot than with Bertrand competition. However, the cost reductions, resulting from the R&D investments, always compensate for the higher R&D investments with Cournot competition by which profits are always higher when firms compete with quantities. The ranking of profits with R&D cooperation is thus the same as for R&D competition. Proposition 4.8 formalizes.

Proposition 4.8. With R&D cooperation, profits are always higher with Cournot than with Bertrand competition.

Proof. First note that $\widetilde{\Pi}_C = \dfrac{\gamma(a-c)(2-\theta)^2}{\Phi_C}$ and $\widetilde{\Pi}_B = \dfrac{\gamma(a-c)(2+\theta)^2(1-\theta)^2}{\Phi_B}$.

From this, it follows that $\widetilde{\Pi}_C - \widetilde{\Pi}_B = \dfrac{2\gamma^2(a-c)^2\left(4-\theta^2\right)^2(1-\theta)^2}{\Phi_C\Phi_B} > 0$, where

$$\Phi_C = \gamma\left(4-\theta^2\right)^2 - (1+\beta)(2-\theta)^2,$$

$$\Phi_B = \gamma\left(4-\theta^2\right)^2\left(1-\theta^2\right) - (1+\beta)(1-\theta)^2(2+\theta)^2.$$

From Proposition 4.8, it thus follows that producer surplus, with R&D cooperation in stage one, is always higher under Cournot competition than under Bertrand competition. As both firms are better off with Cournot competition, it would thus be in their interest to commit to Cournot competition. However, as was argued in section 4.3.3.2, it may be hard or impossible for firms to credibly do so.

As will become clear below, post-innovation production costs can be that much lower under Cournot competition than under Bertrand competition by which the larger producer surplus can exceed the reduction in consumer surplus in Cournot markets compared to Bertrand markets. Consequently, total welfare can be higher with Cournot competition than with Bertrand competition. However, first, consumer surplus is analyzed before total surplus is looked at.

4.4.3.3. Price

For comparing prices under Cournot and Bertrand competition we introduce the following assumption:

$$\gamma < \frac{1+\beta}{4-\theta^2} \tag{AA1}$$

If assumption AA1 holds, the R&D process is relatively 'efficient', as small values for γ imply large cost reductions in unit costs for a given amount of R&D inputs (see section 4.2). A high efficiency of the R&D process corresponds to situations where post-innovative costs under Cournot competition are particularly low in comparison to post-innovation costs under Bertrand competition, as was indicated by Lemma 4.5. As will be shown below this has an important implication. First note that assumption AA1 does not rule out the existence of equilibria:

Lemma 4.6. The set where regularity conditions RR1, RR2, RR4 and assumption AA1 hold is not empty.

Proof. For AA1 and RR4 to hold jointly it is required that $1 < a/c < (2+\theta)/(2-\theta)$ or $2(a-c) < \theta(a+c)$. Indeed, a and c can always be chosen such that this inequality holds. For AA1 and RR1 to hold jointly it is required that $1 > \left[\left(2-\theta^2-\theta\beta\right)^2+\left(2\beta-\theta^2\beta-\theta\right)^2\right] / \left[\left(4-\theta^2\right)\left(1-\theta^2\right)\left(1+\beta^2\right)\right]$, or $\beta > \left(2-\theta^2-\sqrt{\left(4-\theta^2\right)\left(1-\theta^2\right)}\right) \Big/ \theta = f(\theta)$. Note that $f(\theta)$ is continuous and strictly decreasing in $\theta \epsilon]0,1[$, that $\lim_{\theta\to 0} f(\theta)=0$, and that $\lim_{\theta\to 1} f(\theta)=1$. For AA1 and RR2 to hold jointly it is required that $1 > \left[\left(2-\theta\beta\right)^2+\left(2\beta-\theta\right)^2\right] / \left[\left(4-\theta^2\right)\left(1+\beta^2\right)\right]$, or $\beta > \left(2-\sqrt{4-\theta^2}\right) \Big/ \theta = g(\theta)$. Note that $g(\theta)$ is continuous and strictly increasing in $\theta \epsilon]0,1[$, that $\lim_{\theta\to 0} g(\theta)=0$, and that $\lim_{\theta\to 1} g(\theta)=2-\sqrt{3}$.

Figure 4.2 displays the admissible parameter space and assumption AA1 for particular values for a, c and γ. Note that from the proof of Lemma 4.6 it follows that $f(\theta)$-$g(\theta)>0$ $\forall \theta \epsilon]0,1[$. Hence, under assumption AA1 the admissible parameter space is defined by conditions RR1 and RR4.

Now, the main result of the analysis with R&D cooperation in the first stage and Bertrand or Cournot competition in the second stage can be stated:

Proposition 4.9. With R&D cooperation, prices are lower under Cournot competition than under Bertrand competition when the R&D process is efficient, spillovers are high and products are not that differentiated.

Proof. Lower prices obtain under Cournot competition than under Bertrand competition if $\widetilde{Q}_C > \widetilde{Q}_B$, or $\gamma < (1+\beta)/\left(4-\theta^2\right)$.

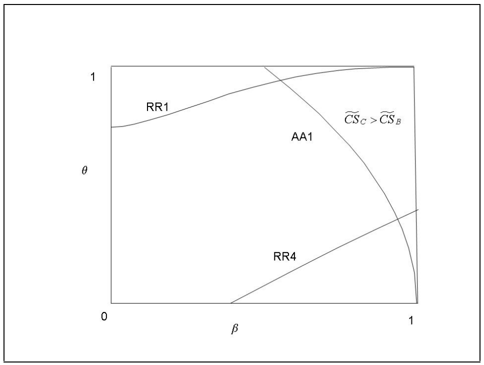

Figure 4.2. Comparing consumer surplus with Cournot and Bertrand competition under assumption AA1 and regularity conditions RR1 and RR4 (a=100, c=70, γ=0.5) with R&D cooperation.

Proposition 4.9 conveys another new message. In a duopoly with substitutable products, prices can be lower under Cournot competition than under Bertrand competition. This happens when post-innovation costs under Cournot competition are sufficiently below post-innovation costs under Bertrand competition, or, in other words, when the difference between R&D investments under Cournot competition and Bertrand competition is sufficiently high. Considering the admissible parameter space in Proposition 4.9, this is the case when the R&D process is efficient, technological spillovers are substantial and products are not that differentiated. It is precisely under these circumstances that Cournot firms invest much more than Bertrand firms and hence the difference between cost reductions in Cournot and Bertrand competition is the largest. Due to these large differences in effective cost reductions, ex post unit costs with Cournot competition are that far below ex post unit costs under Bertrand competition by which it is possible that Bertrand prices exceed Cournot prices. Moreover, note that when prices are lower with Cournot competition, the reverse is true for consumer surplus. Thus, consumers can be better off with Cournot than with Bertrand competition.

In addition, note that condition (AA1) is more likely to hold the larger is β. Indeed, because of the combined profits externality, an R&D cooperative's incentives to invest in R&D are increasing in β. The stronger is then the technological spillover, the more exemplified the difference in R&D investment incentives between Cournot and

Bertrand competition is. Hence, the larger the difference in post-innovation production costs will be.

4.4.3.4. Welfare

From Proposition 4.8, it is known that producer surplus is always higher with Cournot competition than with Bertrand competition. Combining this finding with Proposition 4.9 implies that total surplus can be higher with quantity competition than with price competition. The welfare comparison for the entire parameter space is as follows:

Proposition 4.10. With R&D cooperation, the following applies to the comparison of total surplus with Cournot and Bertrand competition:

(i) Total surplus is higher with Cournot competition than with Bertrand competition when the R&D process is efficient, spillovers are high and products are not that differentiated.

(ii) When the R&D process is not that efficient, total surplus can still be higher with Cournot competition than with Bertrand competition, provided that the R&D process is still efficient enough.

Proof. See Appendix

Part (i) in Proposition 4.10 is the new message in terms of welfare when product market competition is preceded by cooperative investments in cost-reducing R&D. Whenever under Cournot competition price is lower than under Bertrand competition, the reverse holds for total surplus. As producer surplus is always higher with Cournot competition and consumer surplus can also be higher when the R&D process is efficient, it is clear that also total surplus can be higher with an efficient R&D process. This result is not without policy implications. In particular, lower competition intensity (i.e. Cournot competition) can be beneficial for society, even if the market competition is preceded by a stage of cooperative R&D. After all, the lower competition intensity not only stimulates R&D investments, final consumer prices could also be reduced substantially, even below the level that would emerge under a higher intensity of competition in the product market (i.e. Bertrand competition). Part (ii) indicates that when prices are higher with Cournot than with Bertrand competition, total surplus can still be higher with Cournot competition as the higher producer surplus compensates for the lower consumer surplus.

4.5. Implications and concluding remarks

In this chapter, is has been shown that for a duopoly with substitutable goods, cost-reducing R&D investment incentives are always higher in Cournot markets than in Bertrand markets. After all, under Bertrand competition, much more of the benefits of any cost reduction is given to consumers than under Cournot competition, by which Bertrand firms are less eager to invest in R&D compared to Cournot firms. This finding contributes to one of the most debated issues in the literature on innovation, namely the impact of the degree of product market competition on the incentives to engage in R&D activities. This is more or less in line with Schumpeter's argument that less intense market competition (here Cournot competition) is associated with more R&D activity.

To continue, the study here shows that prices can sometimes be lower with Cournot than with Bertrand competition. After all, when the R&D process is efficient, spillovers are substantial and products are not that differentiated, the investments and concomitant cost reductions with Cournot competition are that much higher compared to Bertrand competition by which prices can be lower under Cournot competition than under Bertrand competition. This may occur both with R&D competition and R&D cooperation. Consequently, consumer surplus and total surplus are sometimes higher with Cournot competition than with Bertrand competition. Thus, Cournot markets can, under certain conditions, outperform Bertrand markets, both in terms of innovative activity (higher R&D investments) and, what is new, welfare (higher total surplus).

On the one hand, the theoretical findings here may be used in a positive way as they help to explain some empirical observations. For example, as was mentioned in the introduction of this chapter, the semiconductor industry, in which there is competition with quantities (due to capacity constraints) and in which spillovers tend to be significant (De Bondt and Veugelers, 1989; Gruber, 1998), is characterized by very R&D intensive firms (see a.o. Irwin and Klenow, 1996). Part of these R&D investments aims at reducing their manufacturing costs. Due to these high investments in cost-reducing R&D, prices in the semiconductor industry have been declining sharply to a current level which is rather low (Aizcorbe, 2002), which is thus in line with the findings of this chapter.

On the other hand, the theoretical findings of this chapter may also be used in a normative way as they can be used to inspire policy makers. As firms in Cournot markets are more willing to invest in R&D than in Bertrand markets, an obvious policy instrument to increase private R&D investments might be imposing competition with quantities. However, caution is called for here. Firstly, it is quite hard for governments to impose Bertrand or Cournot competition to a certain industry as the competition mode usually results from the underlying technology. More specifically, capacity constraints tend to drive the competition mode. When capacity constraints are strong, it is hard to expand capacity overnight and Cournot competition prevails, which is for example the case in the agricultural industry. After all, it is just impossible to increase the harvest of potatoes overnight. In other industries, capacity is very flexible, which is for example the case in the market for downloadable music. As has been explained, in this kind of industries, it is hard or impossible for firms to commit to a certain capacity. Secondly, switching from Bertrand to Cournot competition may result in sacrificing social welfare for more innovative activity (except for the case where total surplus is higher with Cournot competition).

Consequently, other policy instruments might be more appropriate to increase R&D investments when there is Bertrand competition[86]. The finding that investments are lower in Bertrand markets compared to Cournot markets suggests that the implementation of policy instruments should be dependent on the market competition mode. Previous studies indeed illustrate that policy instruments need to be tailored to the market competition mode. Poyago-Theotoky (2003), for example argues that emission taxes and the effectiveness of R&D subsidies are different under Cournot and Bertrand competition when the product market competition is preceded by a stage of investments in emission reducing R&D. Moreover, in strategic trade policy models, it has been shown that the optimal level of certain instruments, such as subsidies,

[86] From previous studies, it is known that R&D investments with Cournot and Bertrand competition are smaller than the social optimal investments.

quotas, tariffs and taxes, depends on the competition mode (Eaton and Grossman, 1986; Maggi, 1996).

The model here could be extended to further examine the dependency of certain policy instruments on the competition mode. For example, it could be analyzed how the optimal levels of R&D subsidies are related to Bertrand or Cournot competition. Moreover, it could then be analyzed whether these R&D subsidies reduce or even remove the wedge between Bertrand and Cournot investments.

Finally, attention should also be paid to some limitations of this study. Firstly, the spillover is assumed to be symmetric. However, as argued in the second chapter of this dissertation, spillovers, in general, tend to be asymmetric. Secondly, the analysis could be extended to the scenario where there are more than two firms investing in R&D and competing on the product market.

4.6. References

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Appendix

Decomposition of R&D incentives with R&D competition in the first stage

A. Cournot Competition

The second-stage profits of firm *i* equal:

$$\Pi_i = \pi_i - x_i,$$

$$\text{with } \pi_i = p_i q_i - (c - y_i) q_i .$$

The first order condition for firm *i* in the production stage when firms compete with quantities is:

$$\frac{\partial \pi_i}{\partial q_i} = p_i + q_i \frac{\partial p_i}{\partial q_i} - (c - y_i) = 0 .$$

The second order condition is also satisfied as $\frac{\partial p_i}{\partial q_i} < 0$:

$$\frac{\partial^2 \pi_i}{\partial q_i^2} = 2\frac{\partial p_i}{\partial q_i} + q_i \frac{\partial^2 p_i}{\partial q_i^2} \leq 0 .$$

Furthermore, it is known that

$$\frac{\partial^2 \pi_i}{\partial q_i \partial q_j} = \frac{\partial p_i}{\partial q_j} + q_i \frac{\partial^2 p_i}{\partial q_i \partial q_j},$$

$$\frac{\partial \pi_i}{\partial q_j} = q_i \frac{\partial p_i}{\partial q_j}.$$

In the first stage, the first order condition for firm *i* is:

$$\frac{\partial \Pi_i}{\partial x_i} = \begin{matrix} q_i \frac{\partial p_i}{\partial q_i}\frac{\partial q_i}{\partial x_i} + q_i \frac{\partial p_i}{\partial q_j}\frac{\partial q_j}{\partial x_i} + p_i \frac{\partial q_i}{\partial x_i} + \frac{q_i}{2\gamma y_i} \\ -(c - y_i)\frac{\partial q_i}{\partial x_i} - 1 \end{matrix} = 0 .$$

Rewriting this last equality yields:

$$\frac{\partial \Pi_i}{\partial x_i} = \begin{matrix} \left[p_i + q_i \frac{\partial p_i}{\partial q_i} - (c - y_i) \right] \frac{\partial q_i}{\partial x_i} \\ + q_i \frac{\partial p_i}{\partial q_j}\frac{\partial q_j}{\partial x_i} + \frac{q_i}{2\gamma y_i} - 1 \end{matrix} = 0$$

which can be simplified to:

$$\frac{\partial \Pi_i}{\partial x_i} = \frac{\partial \pi_i}{\partial q_j}\frac{\partial q_j}{\partial x_i} + \frac{\partial \pi_i}{\partial x_i} - 1 .$$

This requires information on $\frac{\partial q_j}{\partial x_i}$.

Differentiating the first order conditions of the production stage to x_i yields:

$$\frac{\partial p_i}{\partial q_i}\frac{\partial q_i}{\partial x_i} + \frac{\partial p_i}{\partial q_j}\frac{\partial q_j}{\partial x_i} + \frac{\partial p_i}{\partial q_i}\frac{\partial q_i}{\partial x_i} + q_i \frac{\partial^2 p_i}{\partial q_i^2}\frac{\partial q_i}{\partial x_i} + q_i \frac{\partial^2 p_i}{\partial q_i \partial q_j}\frac{\partial q_j}{\partial x_i} + \frac{1}{2\gamma y_i} = 0 ,$$

$$\frac{\partial p_j}{\partial q_i}\frac{\partial q_i}{\partial x_i} + \frac{\partial p_j}{\partial q_j}\frac{\partial q_j}{\partial x_i} + \frac{\partial p_j}{\partial q_j}\frac{\partial q_j}{\partial x_i} + q_j \frac{\partial^2 p_j}{\partial q_j^2}\frac{\partial q_j}{\partial x_i} + q_i \frac{\partial^2 p_j}{\partial p_i \partial p_j}\frac{\partial q_i}{\partial x_i} + \beta \frac{1}{2\gamma y_i} = 0 .$$

Rewriting these two equations yields:

$$\left[2\frac{\partial p_i}{\partial q_i} + q_i \frac{\partial^2 p_i}{\partial q_i^2}\right]\frac{\partial q_i}{\partial x_i} + \left[\frac{\partial p_i}{\partial q_j} + q_i \frac{\partial^2 p_i}{\partial q_i \partial q_j}\right]\frac{\partial q_j}{\partial x_i} + \frac{1}{2\gamma y_i} = 0 ,$$

$$\left[\frac{\partial p_j}{\partial q_i} + q_j \frac{\partial^2 p_j}{\partial q_i \partial q_j}\right]\frac{\partial q_i}{\partial x_i} + \left[2\frac{\partial p_j}{\partial q_j} + q_j \frac{\partial^2 p_j}{\partial q_j^2}\right]\frac{\partial q_j}{\partial x_i} + \beta \frac{1}{2\gamma y_j} = 0 .$$

It may be clear that these two equation come down to:

$$\frac{\partial^2 \pi_i}{\partial q_i^2}\frac{\partial q_i}{\partial x_i} + \frac{\partial^2 \pi_i}{\partial q_i \partial q_j}\frac{\partial q_j}{\partial x_i} + \frac{1}{2\gamma y_i} = 0 ,$$

$$\frac{\partial^2 \pi_j}{\partial q_i \partial q_j}\frac{\partial q_i}{\partial x_j} + \frac{\partial^2 \pi_j}{\partial q_j^2}\frac{\partial q_j}{\partial x_i} + \beta \frac{1}{2\gamma y_j} = 0 .$$

From this,

$$\frac{\partial q_j}{\partial x_i} = \frac{y_j \frac{\partial^2 \pi_j}{\partial q_i \partial q_j} - \beta y_i \frac{\partial^2 \pi_i}{\partial q_i^2}}{2\gamma y_i y_j \Psi^C} ,$$

with $\Psi^C = \frac{\partial^2 \pi_i}{\partial q_i^2}\frac{\partial^2 \pi_j}{\partial q_j^2} - \frac{\partial^2 \pi_i}{\partial q_i \partial q_j}\frac{\partial^2 \pi_j}{\partial q_i \partial q_j}$ and $\Psi^C > 0$ (stability condition).

From this:

$$\frac{\partial \Pi_i}{\partial x_i} = \frac{\partial \pi_i}{\partial q_j}\frac{\partial q_j}{\partial x_i} + \frac{\partial \pi_i}{\partial x_i} - 1$$

$$= \frac{y_j \dfrac{\partial^2 \pi_j}{\partial q_i \partial q_j} - \beta y_i \dfrac{\partial^2 \pi_i}{\partial q_i^2}}{2\gamma y_i y_j \Psi^C}$$

$$= \left[\frac{y_j}{2\gamma y_i y_j \Psi^C}\frac{\partial \pi_i}{\partial q_j}\frac{\partial^2 \pi_j}{\partial q_i \partial q_j}\right] + \left[\frac{-\beta y_i}{2\gamma y_i y_j \Psi^C}\frac{\partial \pi_i}{\partial q_j}\frac{\partial^2 \pi_i}{\partial q_i^2}\right] + \frac{q_i}{2\gamma y_i} - 1$$

B. Bertrand competition

The second-stage profits of firm i equal:

$$\Pi_i = \pi_i - x_i,$$

with $\pi_i = p_i q_i - (c - y_i) q_i$.

The first order condition for firm *i* in the production stage when firms compete with prices is:

$$\frac{\partial \pi_i}{\partial p_i} = q_i + p_i \frac{\partial q_i}{\partial p_i} - (c - y_i)\frac{\partial q_i}{\partial p_i}.$$

The second order conditions are also satisfied as $\frac{\partial q_i}{\partial p_i} < 0$:

$$\frac{\partial^2 \pi_i}{\partial p_i^2} = 2\frac{\partial q_i}{\partial p_i} + p_i \frac{\partial^2 q_i}{\partial p_i^2} - (c - y_i)\frac{\partial^2 q_i}{\partial p_i^2} \le 0.$$

Furthermore, it is known that:

$$\frac{\partial^2 \pi_i}{\partial p_i \partial p_j} = \frac{\partial q_i}{\partial p_j} + p_i \frac{\partial^2 q_i}{\partial p_i \partial p_j} - (c - y_i)\frac{\partial^2 q_i}{\partial p_i \partial p_j},$$

$$\frac{\partial \pi_i}{\partial p_j} = p_i \frac{\partial q_i}{\partial p_j} - (c - y_i)\frac{\partial q_i}{\partial p_j}.$$

In the first stage, the first order condition is:

$$\frac{\partial \Pi_i}{\partial x_i} = p_i \frac{\partial q_i}{\partial p_i}\frac{\partial p_i}{\partial x_i} + p_i \frac{\partial q_i}{\partial p_j}\frac{\partial p_j}{\partial x_i} + q_i \frac{\partial p_i}{\partial x_i} + \frac{q_i}{2\gamma y_i}$$
$$-(c-y_i)\frac{\partial q_i}{\partial p_i}\frac{\partial p_i}{\partial x_i} - (c-y_i)\frac{\partial q_i}{\partial p_j}\frac{\partial p_j}{\partial x_i} - 1$$

Rewriting this last inequality yields:

$$\frac{\partial \Pi_i}{\partial x_i} = \left[p_i \frac{\partial q_i}{\partial p_i} + q_i - (c-y_i)\frac{\partial q_i}{\partial p_i}\right]\frac{\partial p_i}{\partial x_i}$$
$$+ p_i \frac{\partial q_i}{\partial p_j}\frac{\partial p_j}{\partial x_i} + \frac{q_i}{2\gamma y_i} - (c-y_i)\frac{\partial q_i}{\partial p_j}\frac{\partial p_j}{\partial x_i} - 1$$

which can be simplified to:

$$\frac{\partial \Pi_i}{\partial x_i} = \frac{\partial \pi_i}{\partial p_j}\frac{\partial p_j}{\partial x_i} + \frac{\partial \pi_i}{\partial x_i} - 1 .$$

This requires information on $\dfrac{\partial p_j}{\partial x_i}$.

Differentiating the first order conditions of the production stage to x_i yields:

$$\begin{aligned}&\frac{\partial q_i}{\partial p_i}\frac{\partial p_i}{\partial x_i} + \frac{\partial q_i}{\partial p_j}\frac{\partial p_j}{\partial x_i} + \frac{\partial q_i}{\partial p_i}\frac{\partial p_i}{\partial x_i} + p_i \frac{\partial^2 q_i}{\partial p_i^2}\frac{\partial p_i}{\partial x_i} + p_i \frac{\partial^2 q_i}{\partial p_i \partial p_j}\frac{\partial p_j}{\partial x_i} \\ &+ \frac{1}{2\gamma y_i}\frac{\partial q_i}{\partial p_i} - (c-y_i)\frac{\partial^2 q_i}{\partial p_i^2}\frac{\partial p_i}{\partial x_i} - (c-y_i)\frac{\partial^2 q_i}{\partial p_i \partial p_j}\frac{\partial p_j}{\partial x_i}\end{aligned} = 0 \text{ and}$$

$$\begin{aligned}&\frac{\partial q_j}{\partial p_i}\frac{\partial p_i}{\partial x_i} + \frac{\partial q_j}{\partial p_j}\frac{\partial p_j}{\partial x_i} + \frac{\partial q_j}{\partial p_j}\frac{\partial p_j}{\partial x_i} + p_j \frac{\partial^2 q_j}{\partial p_j^2}\frac{\partial p_j}{\partial x_i} + p_j \frac{\partial^2 q_j}{\partial p_i \partial p_j}\frac{\partial p_i}{\partial x_i} \\ &+ \frac{\beta}{2\gamma y_j}\frac{\partial q_j}{\partial p_j} - (c-y_j)\frac{\partial^2 q_j}{\partial p_i \partial p_j}\frac{\partial p_i}{\partial x_i} - (c-y_j)\frac{\partial^2 q_j}{\partial p_j^2}\frac{\partial p_j}{\partial x_i}\end{aligned} = 0.$$

Rewriting these two equations yields:

$$\begin{aligned}&\left[2\frac{\partial q_i}{\partial p_i} + p_i \frac{\partial^2 q_i}{\partial p_i^2} - (c-y_i)\frac{\partial^2 q_i}{\partial p_i^2}\right]\frac{\partial p_i}{\partial x_i} \\ &+ \left[\frac{\partial q_i}{\partial p_j} + p_i \frac{\partial^2 q_i}{\partial p_i \partial p_j} - (c-y_i)\frac{\partial^2 q_i}{\partial p_i \partial p_j}\right]\frac{\partial p_j}{\partial x_i} + \frac{1}{2\gamma y_i}\frac{\partial q_i}{\partial p_i} = 0\end{aligned} \quad \text{and}$$

$$\left[\frac{\partial q_j}{\partial p_i}+p_j\frac{\partial^2 q_j}{\partial p_i \partial p_j}-\left(c-y_j\right)\frac{\partial^2 q_2}{\partial p_1 \partial p_2}\right]\frac{\partial p_1}{\partial x_1}$$
$$+\left[2\frac{\partial q_2}{\partial p_2}+p_2\frac{\partial^2 q_2}{\partial p_2^2}-\left(c-y_j\right)\frac{\partial^2 q_j}{\partial p_j^2}\right]\frac{\partial p_j}{\partial x_i}+\frac{\beta}{2\gamma y_j}\frac{\partial q_j}{\partial p_j}=0$$

Further rewriting yields:

$$\frac{\partial^2 \pi_i}{\partial p_i^2}\frac{\partial p_i}{\partial x_i}+\frac{\partial^2 \pi_i}{\partial p_i \partial p_j}\frac{\partial p_j}{\partial x_i}+\frac{1}{2\gamma y_i}\frac{\partial q_i}{\partial p_i}=0 \text{ and}$$

$$\frac{\partial^2 \pi_j}{\partial p_i \partial p_j}\frac{\partial p_i}{\partial x_i}+\frac{\partial^2 \pi_j}{\partial p_j^2}\frac{\partial p_j}{\partial x_i}+\frac{\beta}{2\gamma y_j}\frac{\partial q_j}{\partial p_j}=0.$$

From this:

$$\frac{\partial p_j}{\partial x_i}=\frac{y_j\frac{\partial^2 \pi_j}{\partial p_i \partial p_j}\frac{\partial q_i}{\partial p_i}-\beta y_i\frac{\partial^2 \pi_i}{\partial p_i^2}\frac{\partial q_j}{\partial p_j}}{2\gamma y_i y_j \Psi^B},$$

with $\Psi^B=\frac{\partial^2 \pi_i}{\partial p_i^2}\frac{\partial^2 \pi_j}{\partial p_j^2}-\frac{\partial^2 \pi_i}{\partial p_i \partial p_j}\frac{\partial^2 \pi_j}{\partial p_i \partial p_j}$ and $\Psi^B>0$ (stability condition).

From this:

$$\frac{\partial \Pi_i}{\partial x_i}=\frac{\partial \pi_i}{\partial p_j}\frac{\partial p_j}{\partial x_i}+\frac{\partial \pi_i}{\partial x_i}-1$$
$$\frac{y_j\frac{\partial^2 \pi_j}{\partial p_i \partial p_j}\frac{\partial q_i}{\partial p_i}-\beta\frac{\partial^2 \pi_i}{\partial p_i^2}\frac{\partial q_j}{\partial p_j}}{2\gamma y_1 y_2 \Psi^B}.$$
$$=\left[\frac{y_j}{2\gamma y_i y_j \Psi^B}\frac{\partial \pi_i}{\partial p_j}\frac{\partial^2 \pi_j}{\partial p_i \partial p_j}\frac{\partial q_i}{\partial p_i}\right]+\left[\frac{-\beta y_i}{2\gamma y_i y_j \Psi^B}\frac{\partial \pi_i}{\partial p_j}\frac{\partial^2 \pi_i}{\partial p_i^2}\frac{\partial q_j}{\partial p_j}\right]+\frac{q_i}{2\gamma y_i}-1$$

Proof of Proposition 4.5.

First not that:

$$\widetilde{TS}_B-\widetilde{TS}_C=\frac{\gamma\left(a-c\right)^2}{\Delta_B^2\Delta_C^2}F\left(\gamma,\theta\right),$$

where $\Delta_B = \gamma(1+\theta)(2-\theta)\left(4-\theta^2\right)-\left(2-\theta^2\right)$,

$\Delta_C = \gamma(2+\theta)\left(4-\theta^2\right)-2$, and

$$F(\gamma,\theta)=\left[\gamma\left(4-\theta^2\right)^2(1+\theta)(3-2\theta)-2\left(2-\theta^2\right)^2\right]\Delta_C^2-\left[\gamma\left(4-\theta^2\right)^2(3+\theta)-8\right]\Delta_B^2$$

Define $G(\gamma,\theta)=F(\gamma,\theta)\Big/\left(\gamma\left(4-\theta^2\right)\right)$.

Obviously, $sign\left(\widetilde{TS}_B-\widetilde{TS}_C\right)=sign\left(G(\gamma,\theta)\right)$. Note that $G(\gamma,\theta)=\gamma^2 g_1+\gamma g_2+g_3$,

where $g_1=\left(4-\theta^2\right)^3(1+\theta)\left(4-2\theta-\theta^2\right)$,

$g_2=-2\left(4-\theta^2\right)^2(1+\theta)\left(4-\theta-\theta^2\right)+2\theta\left(4-\theta^2\right)\left(8+4\theta-4\theta^2-\theta^3\right)$, and

$g_3=\left(4-\theta^2\right)\left(4+4\theta-3\theta^2-\theta^3\right)-8\theta\left(2-\theta^2\right)$.

It follows that $G(\gamma,\theta)$ is strictly convex in γ as $\partial^2 G(\gamma,\theta)\big/\partial\gamma^2=2g_1>0$ (indeed: $\min_{\{\theta\}} g_1=54$). Moreover, $g_2^2-4g_1g_3>0\ \forall\,\theta\in]0,1[$. Hence, given any $\theta\in]0,1[$, there are two real solutions to $G(\gamma,\theta)=0$, particular:

$$\bar{\gamma}_1(\theta)=\frac{-g_1-\sqrt{g_2^2-4g_1g_3}}{2g_1},\ \text{and}\qquad \bar{\gamma}_2(\theta)=\frac{-g_1+\sqrt{g_2^2-4g_1g_3}}{2g_1}.$$

When $\beta=0$, regularity condition R5 is most binding. Label the resulting threshold value on the efficiency parameter $y*$. The result then follows as $\min_{\{\theta\}}\left\{\gamma^*-\bar{\gamma}_2(\theta)\right\}=\lim_{\theta\to 0}\left\{\gamma^*-\bar{\gamma}_2(\theta)\right\}=0$, (see also figure 4.3).

Proof of Proposition 4.6.

This proof is a general version of that in the previous section *Proof of Proposition 4.5* of this appendix. Observe that:

$$\widetilde{TS}_B-\widetilde{TS}_C=\frac{\gamma(a-c)^2}{(1+\beta)\Delta_B^2\Delta_C^2}F(\gamma,\beta,\theta),$$

where $\Delta_B=\gamma(1+\theta)(2-\theta)\left(4-\theta^2\right)-\left(2-\theta^2-\theta\beta\right)$,

$\Delta_C=\gamma(2+\theta)\left(4-\theta^2\right)-(2-\theta\beta)$, and

$$F(\gamma,\beta,\theta)=\frac{\left[\gamma(1+\beta)\left(4-\theta^2\right)^2(1+\theta)(3-2\theta)-2\left(2-\theta^2-\theta\beta\right)^2\right]\Delta_C^2}{-\left[\gamma(1+\beta)\left(4-\theta^2\right)^2(3+\theta)-2(2-\theta\beta)\right]\Delta_B^2}.$$

Again, the related function $G(\gamma,\beta,\theta)=F(\gamma,\beta,\theta)/\left(\gamma\left(4-\theta^2\right)\right)$ is considered. It follows that $sign\left(\widetilde{TS}_B-\widetilde{TS}_C\right)=sign\left(G(\gamma,\beta,\theta)\right)$.

Note that $G(\gamma,\beta,\theta)=\gamma^2 g_1+\gamma g_2+g_3$,

where $g_1=(1+\beta)\left(4-\theta^2\right)^3(1+\theta)\left(4-2\theta-\theta^2\right)$,

$$g_2=-2(1+\beta)\left(4-\theta^2\right)^2(1+\theta)\left(4-\theta(1-\beta)-\theta^2\right) +2\left(4-\theta^2\right)\left[\left(4+2\theta-\theta^2\right)(2-\theta\beta)^2-(2+\theta)^2\left(4-2\theta\beta-\theta^2\right)\right],$$ and

$$g_3=(1+\beta)\left(4-\theta^2\right)\left[2(2-\theta\beta)(1+\theta+\theta\beta)-(3+\theta)\theta^2\right] -4\theta(1+\beta)(2-\theta\beta)\left(2-\theta^2-\theta\beta\right).$$

Then, note that $G(\gamma,\beta,\theta)$ is strictly convex in γ as $\partial^2G(\gamma,\beta,\theta)/\partial\gamma^2=2g_1>0$ (indeed: $\min_{\{\theta,\beta\}}g_1=54$). Moreover, $g_2^2-4g_1g_3>0\ \forall\ \theta\ \epsilon]0,1[$. Hence, given any $\theta\epsilon]0,1[$, there are two real solutions to $G(\gamma,\beta,\theta)=0$, more in particular:

$$\bar{\gamma}_1(\theta)=\frac{-g_1-\sqrt{g_2^2-4g_1g_3}}{2g_1},\ \text{and}\qquad \bar{\gamma}_2(\theta)=\frac{-g_1+\sqrt{g_2^2-4g_1g_3}}{2g_1}.$$

Only the larger root needs to be considered as

$$\min_{\{\theta,\beta\}}\left\{\gamma^*-\bar{\gamma}_1(\theta)\right\}=\lim_{\theta\to 0}\left\{\gamma^*-\bar{\gamma}_1(\theta)\right\}\Big|_{\beta=1}=0,$$

where γ^* is the threshold value induced by R7. Label this larger root $\bar{\gamma}(\theta)$. Then observe that $\min_{\{\theta,\beta\}}\left\{\partial\bar{\gamma}(\theta)/\partial\beta\right\}=\lim_{\theta\to 0}\partial\bar{\gamma}(\theta)/\partial\beta\Big|_{\beta=0.5}=0$. This gives rise to the different lines as drawn in figure 4.3 for different values of β. Obviously, for any $\gamma<\bar{\gamma}(\theta)$ we are in situation (i) while situation (ii) emerges for any $\gamma>\bar{\gamma}(\theta)$. The rest of the proof then follows.

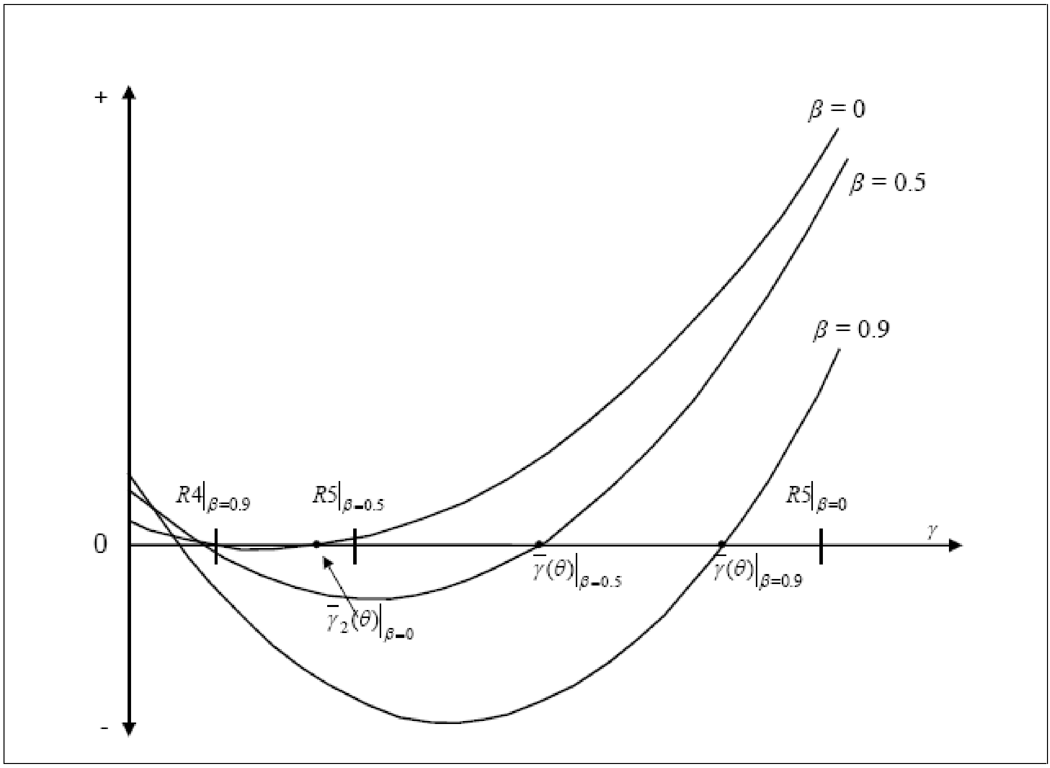

Figure 4.3. $G(\gamma,\beta,\theta)$ for different levels of R&D input spillovers: *a*=100, *c*=70 and *θ*=0.9.

Decomposition of R&D incentives with R&D competition in first stage

A. Cournot Competition

The second-stage profits of firm *i* equal:

$$\Pi_i = \pi_i - x_i,$$

with $\pi_i = p_i q_i - (c - y_i) q_i$.

The first order condition for firm *i* the production stage when firms compete with quantities is:

$$\frac{\partial \Pi_i}{\partial q_i} = p_i + q_i \frac{\partial p_i}{\partial q_i} - (c - y_i).$$

The second order condition is also satisfied as $\frac{\partial p_i}{\partial q_i} < 0$:

$$\frac{\partial^2 \pi_i}{\partial q_i^2} = 2\frac{\partial p_i}{\partial q_i} + q_i \frac{\partial^2 p_i}{\partial q_i^2} \leq 0 .$$

Furthermore, it is known that

$$\frac{\partial^2 \pi_i}{\partial q_i \partial q_j} = \frac{\partial p_i}{\partial q_j} + q_i \frac{\partial^2 p_i}{\partial q_i \partial q_j} ,$$

$$\frac{\partial \pi_i}{\partial q_j} = q_i \frac{\partial p_i}{\partial q_j} .$$

In the first stage, the first order condition, with $\Pi_T = \Pi_i + \Pi_j$, is:

$$\begin{aligned}\frac{\partial \Pi_T}{\partial x_i} = {} & q_i \frac{\partial p_i}{\partial q_i}\frac{\partial q_i}{\partial x_i} + q_i \frac{\partial p_i}{\partial q_j}\frac{\partial q_j}{\partial x_i} + p_i \frac{\partial q_i}{\partial x_i} + \frac{q_i}{2\gamma y_i} \\ & -(c - y_i)\frac{\partial q_i}{\partial x_i} - 1 \\ & + q_j \frac{\partial p_j}{\partial q_i}\frac{\partial q_i}{\partial x_i} + q_j \frac{\partial p_j}{\partial q_j}\frac{\partial q_j}{\partial x_i} + p_j \frac{\partial q_j}{\partial x_i} + \frac{\beta q_j}{2\gamma y_j} \\ & -(c - y_j)\frac{\partial q_j}{\partial x_i}\end{aligned}$$

Rewriting this first order condition yields:

$$\begin{aligned}\frac{\partial \Pi_T}{\partial x_i} = {} & \left[p_i + q_i \frac{\partial p_i}{\partial q_i} - (c - y_i) \right] \frac{\partial q_i}{\partial x_i} \\ & + q_i \frac{\partial p_i}{\partial q_j}\frac{\partial q_j}{\partial x_i} + \frac{q_i}{2\gamma y_i} - 1 \\ & + \left[p_j + q_j \frac{\partial p_j}{\partial q_j} - (c - y_j) \right] \frac{\partial q_j}{\partial x_i} \\ & + q_j \frac{\partial p_j}{\partial q_i}\frac{\partial q_i}{\partial x_i} + \frac{\beta q_j}{2\gamma y_j}\end{aligned}$$

By using the first order condition of the production stage, further rewriting brings:

$$\frac{\partial \Pi_T}{\partial x_i} = \frac{\partial \pi_i}{\partial q_j}\frac{\partial q_j}{\partial x_i} + \frac{\partial \pi_j}{\partial q_i}\frac{\partial q_i}{\partial x_i} + \frac{\partial \pi_i}{\partial x_i} + \frac{\partial \pi_j}{\partial x_i} - 1$$

This requires information on $\frac{\partial q_i}{\partial x_i}$ and $\frac{\partial q_j}{\partial x_i}$.

Differentiating the first order conditions of the production stage to x_i yields:

$$\frac{\partial p_i}{\partial q_i}\frac{\partial q_i}{\partial x_i}+\frac{\partial p_i}{\partial q_j}\frac{\partial q_j}{\partial x_i}+\frac{\partial p_i}{\partial q_i}\frac{\partial q_i}{\partial x_i}+q_i\frac{\partial^2 p_i}{\partial q_i^2}\frac{\partial q_i}{\partial x_i}+q_i\frac{\partial^2 p_i}{\partial q_i \partial q_j}\frac{\partial q_j}{\partial x_i}+\frac{1}{2\gamma y_i}=0 \text{ and}$$

$$\frac{\partial p_j}{\partial q_i}\frac{\partial q_i}{\partial x_i}+\frac{\partial p_j}{\partial q_j}\frac{\partial q_j}{\partial x_i}+\frac{\partial p_j}{\partial q_j}\frac{\partial q_j}{\partial x_i}+q_j\frac{\partial^2 p_j}{\partial q_j^2}\frac{\partial q_j}{\partial x_i}+q_j\frac{\partial^2 p_j}{\partial p_i \partial p_j}\frac{\partial q_i}{\partial x_i}+\beta\frac{1}{2\gamma y_i}=0.$$

Rewriting these two expressions yields:

$$\left[2\frac{\partial p_i}{\partial q_i}+q_i\frac{\partial^2 p_i}{\partial q_i^2}\right]\frac{\partial q_i}{\partial x_i}+\left[\frac{\partial p_i}{\partial q_j}+q_i\frac{\partial^2 p_i}{\partial q_i \partial q_j}\right]\frac{\partial q_j}{\partial x_i}+\frac{1}{2\gamma y_i}=0 \text{ and}$$

$$\left[\frac{\partial p_j}{\partial q_i}+q_j\frac{\partial^2 p_j}{\partial q_i \partial q_j}\right]\frac{\partial q_i}{\partial x_i}+\left[2\frac{\partial p_j}{\partial q_j}+q_j\frac{\partial^2 p_j}{\partial q_j^2}\right]\frac{\partial q_j}{\partial x_i}+\frac{\beta}{2\gamma y_j}=0.$$

Rewriting these two equations yields:

$$\frac{\partial^2 \pi_i}{\partial q_i^2}\frac{\partial q_i}{\partial x_i}+\frac{\partial^2 \pi_i}{\partial q_i \partial q_j}\frac{\partial q_j}{\partial x_i}+\frac{1}{2\gamma y_i}=0 \text{ and}$$

$$\frac{\partial^2 \pi_j}{\partial q_i \partial q_j}\frac{\partial q_i}{\partial x_i}+\frac{\partial^2 \pi_j}{\partial q_j^2}\frac{\partial q_j}{\partial x_i}+\frac{\beta}{2\gamma y_j}=0$$

From this,

$$\frac{\partial q_i}{\partial x_i}=\frac{\beta y_i\frac{\partial^2 \pi_i}{\partial q_i \partial q_j}-y_j\frac{\partial^2 \pi_j}{\partial q_j^2}}{2\gamma y_i y_j \Psi^C},$$

$$\frac{\partial q_j}{\partial x_i}=\frac{y_j\frac{\partial^2 \pi_j}{\partial q_i \partial q_j}-\beta y_i\frac{\partial^2 \pi_i}{\partial q_i^2}}{2\gamma y_i y_j \Psi^C},$$

with $\Psi^C=\frac{\partial^2 \pi_i}{\partial q_i^2}\frac{\partial^2 \pi_j}{\partial q_j^2}-\frac{\partial^2 \pi_i}{\partial q_i \partial q_j}\frac{\partial^2 \pi_j}{\partial q_i \partial q_j}$ and $\Psi^C>0$ (stability condition).

$$\frac{\partial \Pi_T}{\partial x_i} = \frac{\partial \pi_i}{\partial q_j}\frac{\partial q_j}{\partial x_i} + \frac{\partial \pi_j}{\partial q_i}\frac{\partial q_i}{\partial x_i} + \frac{\partial \pi_i}{\partial x_i} + \frac{\partial \pi_j}{\partial x_i} - 1$$

$$= \left[\frac{y_j}{2\gamma y_i y_j \Psi^C}\frac{\partial \pi_i}{\partial q_j}\frac{\partial^2 \pi_j}{\partial q_i \partial q_j} - \frac{y_j}{2\gamma y_i y_j \Psi^C}\frac{\partial \pi_j}{\partial q_i}\frac{\partial^2 \pi_j}{\partial q_j^2}\right]$$

$$+ \left[\frac{\beta y_i}{2\gamma y_i y_j \Psi^C}\frac{\partial \pi_j}{\partial q_i}\frac{\partial^2 \pi_i}{\partial q_i \partial q_j} - \frac{\beta y_i}{2\gamma y_i y_j \Psi^C}\frac{\partial \pi_i}{\partial q_j}\frac{\partial^2 \pi_i}{\partial q_i^2}\right]$$

$$+ \frac{q_i}{2\gamma y_i} + \frac{\beta q_j}{2\gamma y_j} - 1$$

Finally,

$$\frac{\partial \Pi_T}{\partial x_i} = \left[\frac{y_j}{2\gamma y_i y_j \Psi^C}\left(\left[\frac{\partial \pi_i}{\partial q_j}\frac{\partial^2 \pi_j}{\partial q_i \partial q_j}\right] + \left[-\frac{\partial \pi_j}{\partial q_j}\frac{\partial^2 \pi_j}{\partial q_j^2}\right]\right)\right] +$$

$$\left[\frac{\beta y_i}{2\gamma y_i y_j \Psi^C}\left(\left[\frac{\partial \pi_j}{\partial q_i}\frac{\partial^2 \pi_i}{\partial q_i \partial q_j}\right] + \left[-\frac{\partial \pi_i}{\partial q_j}\frac{\partial^2 \pi_i}{\partial q_j^2}\right]\right)\right]$$

$$+ \frac{q_i}{2\gamma y_i} + \frac{\beta q_j}{2\gamma y_j} - 1$$

It is known that:

$\frac{\partial \pi_i}{\partial q_j} < 0$, $\frac{\partial \pi_j}{\partial q_i} < 0$ and $\frac{\partial \pi_i}{\partial q_j} = \frac{\partial \pi_j}{\partial q_i}$ (Slutsky),

$\frac{\partial^2 \pi_i}{\partial q_i \partial q_j} < 0$, $\frac{\partial^2 \pi_j}{\partial q_i \partial q_j}$ and $\frac{\partial^2 \pi_i}{\partial q_i \partial q_j} = \frac{\partial^2 \pi_j}{\partial q_i \partial q_j}$,

$\frac{\partial^2 \pi_i}{\partial q_i^2} < 0$, $\frac{\partial^2 \pi_j}{\partial q_j^2} < 0$ and $\frac{\partial^2 \pi_i}{\partial q_i^2} = \frac{\partial^2 \pi_j}{\partial q_j^2}$ (second order conditions),

$\frac{\partial^2 \pi_i}{\partial q_i^2} = \frac{\partial^2 \pi_j}{\partial q_j^2} < \frac{\partial^2 \pi_i}{\partial q_i \partial q_j} = \frac{\partial^2 \pi_j}{\partial q_i \partial q_j}$ (stability condition strategic substitutes).

This information satisfies to derive the signs of the strategic, spillover, size and cost effect.

B. Bertrand Competition

The second stage profits are:

$$\Pi_i = p_i q_i - (c - y_i) q_i - x_i,$$

with $\pi_i = p_i q_i - (c - y_i) q_i$.

The first order condition for firm i in the production stage when firms compete with prices is:

$$\frac{\partial \pi_i}{\partial p_i} = q_i + p_i \frac{\partial q_i}{\partial p_i} - (c - y_i) \frac{\partial q_i}{\partial p_i}.$$

The second order conditions are also satisfied as $\frac{\partial q_i}{\partial p_i} < 0$

$$\frac{\partial^2 \pi_i}{\partial p_i^2} = 2 \frac{\partial q_i}{\partial p_i} + p_i \frac{\partial^2 q_i}{\partial p_i^2} - (c - y_i) \frac{\partial^2 q_i}{\partial p_i^2} \leq 0.$$

Furthermore, it is known that

$$\frac{\partial^2 \pi_i}{\partial p_i \partial p_j} = \frac{\partial q_i}{\partial p_j} + p_i \frac{\partial^2 q_i}{\partial p_i \partial p_j} - (c - y_i) \frac{\partial^2 q_i}{\partial p_i \partial p_j},$$

$$\frac{\partial \pi_i}{\partial p_j} = p_i \frac{\partial q_i}{\partial p_j} - (c - y_i) \frac{\partial q_i}{\partial p_j}.$$

In the first stage, the first order condition is:

$$\begin{aligned}
\frac{\partial \Pi_T}{\partial x_i} = {} & p_i \frac{\partial q_i}{\partial p_i} \frac{\partial p_i}{\partial x_i} + p_i \frac{\partial q_i}{\partial p_j} \frac{\partial p_j}{\partial x_i} + q_i \frac{\partial p_i}{\partial x_i} + \frac{q_i}{2\gamma y_i} \\
& - (c - y_i) \frac{\partial q_i}{\partial p_i} \frac{\partial p_i}{\partial x_i} - (c - y_i) \frac{\partial q_i}{\partial p_j} \frac{\partial p_j}{\partial x_i} - 1 \\
& + p_j \frac{\partial q_j}{\partial p_i} \frac{\partial p_i}{\partial x_i} + p_j \frac{\partial q_j}{\partial p_j} \frac{\partial p_j}{\partial x_i} + q_j \frac{\partial p_j}{\partial x_i} + \frac{\beta q_j}{2\gamma y_j} \\
& - (c - y_j) \frac{\partial q_j}{\partial p_i} \frac{\partial p_i}{\partial x_i} - (c - y_j) \frac{\partial q_j}{\partial p_j} \frac{\partial p_j}{\partial x_i}
\end{aligned}$$

or after rewriting:

$$
\begin{aligned}
\frac{\partial \Pi_T}{\partial x_i} = & \left[p_i \frac{\partial q_i}{\partial p_i} + q_i - (c - y_i) \frac{\partial q_i}{\partial p_i} \right] \frac{\partial p_i}{\partial x_i} \\
& + \left[p_j \frac{\partial q_j}{\partial p_j} + q_j - (c - y_j) \frac{\partial q_j}{\partial p_j} \right] \frac{\partial p_j}{\partial x_i} \\
& + p_i \frac{\partial q_i}{\partial p_j} \frac{\partial p_j}{\partial x_i} + \frac{q_i}{2\gamma y_i} - (c - y_i) \frac{\partial q_i}{\partial p_j} \frac{\partial p_j}{\partial x_i} - 1 \\
& + p_j \frac{\partial q_j}{\partial p_i} \frac{\partial p_i}{\partial x_i} + \frac{\beta q_j}{2\gamma y_i} - (c - y_j) \frac{\partial q_j}{\partial p_i} \frac{\partial p_i}{\partial x_i}
\end{aligned}
$$

Using the first order conditions of the production stage:

$$
\frac{\partial \Pi_T}{\partial x_i} = \left[p_i \frac{\partial q_i}{\partial p_j} - (c - y_i) \frac{\partial q_i}{\partial p_j} \right] \frac{\partial p_j}{\partial x_i} + \left[p_j \frac{\partial q_j}{\partial p_i} - (c - y_j) \frac{\partial q_j}{\partial p_i} \right] \frac{\partial p_i}{\partial x_i} + \frac{q_i}{2\gamma y_i} + \frac{\beta q_j}{2\gamma y_j} - 1
$$

.

Thus: $\frac{\partial \Pi_T}{\partial x_i} = \frac{\partial \pi_i}{\partial p_j} \frac{\partial p_j}{\partial x_i} + \frac{\partial \pi_i}{\partial x_i} + \frac{\partial \pi_j}{\partial p_i} \frac{\partial p_i}{\partial x_i} + \frac{\partial \pi_j}{\partial x_i} - 1$.

This requires information on $\frac{\partial p_i}{\partial x_i}$ and $\frac{\partial p_j}{\partial x_i}$.

Differentiating the first order conditions of the production stage to x_i yields:

$$
\begin{aligned}
& \frac{\partial q_i}{\partial p_i} \frac{\partial p_i}{\partial x_i} + \frac{\partial q_i}{\partial p_j} \frac{\partial p_j}{\partial x_i} + \frac{\partial q_i}{\partial p_i} \frac{\partial p_i}{\partial x_i} + p_i \frac{\partial^2 q_i}{\partial p_i^2} \frac{\partial p_i}{\partial x_i} + p_i \frac{\partial^2 q_i}{\partial p_i \partial p_j} \frac{\partial p_j}{\partial x_i} \\
& + \frac{1}{2\gamma y_i} \frac{\partial q_i}{\partial p_i} - (c - y_i) \frac{\partial^2 q_i}{\partial p_i^2} \frac{\partial p_i}{\partial x_i} - (c - y_i) \frac{\partial^2 q_i}{\partial p_i \partial p_j} \frac{\partial p_j}{\partial x_i}
\end{aligned}
=0 \text{ and}
$$

$$
\begin{aligned}
& \frac{\partial q_j}{\partial p_i} \frac{\partial p_i}{\partial x_i} + \frac{\partial q_j}{\partial p_j} \frac{\partial p_j}{\partial x_i} + \frac{\partial q_j}{\partial p_j} \frac{\partial p_j}{\partial x_i} + p_j \frac{\partial^2 q_j}{\partial p_j^2} \frac{\partial p_j}{\partial x_i} + p_j \frac{\partial^2 q_j}{\partial p_i \partial p_j} \frac{\partial p_i}{\partial x_i} \\
& + \frac{\beta}{2\gamma y_j} \frac{\partial q_j}{\partial p_j} - (c - y_j) \frac{\partial^2 q_j}{\partial p_i \partial p_j} \frac{\partial p_i}{\partial x_i} - (c - y_j) \frac{\partial^2 q_j}{\partial p_j^2} \frac{\partial p_j}{\partial x_i}
\end{aligned}
=0
$$

Rewriting yields:

$$\left.\begin{aligned}&\left[2\frac{\partial q_i}{\partial p_i}+p_i\frac{\partial^2 q_i}{\partial p_i^2}-(c-y_i)\frac{\partial^2 q_i}{\partial p_i^2}\right]\frac{\partial p_i}{\partial x_i}\\&+\left[\frac{\partial q_i}{\partial p_j}+p_i\frac{\partial^2 q_i}{\partial p_i\partial p_j}-(c-y_i)\frac{\partial^2 q_i}{\partial p_i\partial p_j}\right]\frac{\partial p_j}{\partial x_i}+\frac{1}{2\gamma y_i}\frac{\partial q_i}{\partial p_i}\end{aligned}\right. = 0 \text{ and}$$

$$\left.\begin{aligned}&\left[\frac{\partial q_j}{\partial p_i}+p_j\frac{\partial^2 q_j}{\partial p_i\partial p_j}-(c-y_j)\frac{\partial^2 q_j}{\partial p_i\partial p_j}\right]\frac{\partial p_1}{\partial x_i}\\&+\left[2\frac{\partial q_j}{\partial p_j}+p_j\frac{\partial^2 q_j}{\partial p_j^2}-(c-y_j)\frac{\partial^2 q_j}{\partial p_j^2}\right]\frac{\partial p_j}{\partial x_i}+\frac{\beta}{2\gamma y_j}\frac{\partial q_j}{\partial p_j}\end{aligned}\right. = 0$$

Rewriting yields:

$$\frac{\partial^2 \pi_i}{\partial p_i^2}\frac{\partial p_i}{\partial x_i}+\frac{\partial^2 \pi_i}{\partial p_i\partial p_j}\frac{\partial p_j}{\partial x_i}+\frac{1}{2\gamma y_i}\frac{\partial q_i}{\partial p_i}=0 \text{ and}$$

$$\frac{\partial^2 \pi_j}{\partial p_i\partial p_j}\frac{\partial p_i}{\partial x_i}+\frac{\partial^2 \pi_j}{\partial p_j^2}\frac{\partial p_j}{\partial x_i}+\frac{\beta}{2\gamma y_j}\frac{\partial q_j}{\partial p_j}=0.$$

From this,

$$\frac{\partial p_i}{\partial x_i}=\frac{\beta y_i\frac{\partial^2 \pi_i}{\partial p_i\partial p_j}\frac{\partial q_j}{\partial p_j}-y_j\frac{\partial^2 \pi_j}{\partial p_j^2}\frac{\partial q_i}{\partial p_i}}{2\gamma y_i y_j \Psi^B} \text{ and}$$

$$\frac{\partial p_j}{\partial x_i}=\frac{y_j\frac{\partial^2 \pi_j}{\partial p_i\partial p_j}\frac{\partial q_i}{\partial p_i}-\beta y_i\frac{\partial^2 \pi_i}{\partial p_i^2}\frac{\partial q_j}{\partial p_j}}{2\gamma y_i y_j \Psi^B},$$

with $\Psi^B=\frac{\partial^2 \pi_i}{\partial p_i^2}\frac{\partial^2 \pi_j}{\partial p_j^2}-\frac{\partial^2 \pi_i}{\partial p_i\partial p_j}\frac{\partial^2 \pi_j}{\partial p_i\partial p_j}$ and $\Psi^B>0$ (stability condition).

Consequently,

$$\frac{\partial \Pi_T}{\partial x_i} = \frac{\partial \pi_i}{\partial p_j}\frac{\partial p_j}{\partial x_i} + \frac{\partial \pi_i}{\partial x_i} + \frac{\partial \pi_j}{\partial p_i}\frac{\partial p_i}{\partial x_i} + \frac{\partial \pi_j}{\partial x_i} - 1$$

$$= \left[\frac{y_j}{2\gamma y_i y_j \Psi^B} \frac{\partial^2 \pi_j}{\partial p_i \partial p_j} \frac{\partial q_i}{\partial p_i} \frac{\partial \pi_i}{\partial p_j} - \frac{y_j}{2\gamma y_i y_j \Psi^B} \frac{\partial \pi_j}{\partial p_i} \frac{\partial^2 \pi_j}{\partial p_j^2} \frac{\partial q_i}{\partial p_i} \right] +$$

$$\left[\frac{\beta y_i}{2\gamma y_i y_j \Psi^B} \frac{\partial \pi_j}{\partial p_i} \frac{\partial^2 \pi_i}{\partial p_i \partial p_j} \frac{\partial q_j}{\partial p_j} - \frac{\beta y_i}{2\gamma y_i y_j \Psi^B} \frac{\partial \pi_i}{\partial p_j} \frac{\partial^2 \pi_i}{\partial p_i^2} \frac{\partial q_j}{\partial p_j} \right]$$

$$+ \frac{q_i}{2\gamma y_i} + \frac{\beta q_j}{2\gamma y_j} - 1$$

Finally:

$$\frac{\partial \Pi_T}{\partial x_i} = \left[\frac{y_j}{2\gamma y_i y_j \Psi^B} \frac{\partial q_i}{\partial p_i} \left(\frac{\partial^2 \pi_j}{\partial p_i \partial p_j} \frac{\partial \pi_i}{\partial p_j} - \frac{\partial \pi_j}{\partial p_i} \frac{\partial^2 \pi_j}{\partial p_j^2} \right) \right] +$$

$$\left[\frac{\beta y_i}{2\gamma y_i y_j \Psi^B} \frac{\partial q_j}{\partial p_j} \left(\frac{\partial \pi_j}{\partial p_i} \frac{\partial^2 \pi_i}{\partial p_i \partial p_j} - \frac{\partial \pi_i}{\partial p_j} \frac{\partial^2 \pi_i}{\partial p_i^2} \right) \right]$$

$$+ \frac{q_i}{2\gamma y_i} + \frac{\beta q_j}{2\gamma y_j} - 1$$

It is known that:

$\frac{\partial \pi_i}{\partial p_j} > 0$, $\frac{\partial \pi_j}{\partial p_i} > 0$ and $\frac{\partial \pi_i}{\partial p_j} = \frac{\partial \pi_j}{\partial p_i}$ (Slutsky),

$\frac{\partial^2 \pi_i}{\partial p_i \partial p_j} > 0$, $\frac{\partial^2 \pi_j}{\partial p_i \partial p_j} > 0$ and $\frac{\partial^2 \pi_i}{\partial p_i \partial p_j} = \frac{\partial^2 \pi_j}{\partial p_i \partial p_j}$ (strategic complements),

$\frac{\partial^2 \pi_i}{\partial p_i^2} < 0$, $\frac{\partial^2 \pi_j}{\partial p_j^2} < 0$ and $\frac{\partial^2 \pi_i}{\partial p_i^2} = \frac{\partial^2 \pi_j}{\partial p_j^2}$ (second order conditions),

$\frac{\partial^2 \pi_i}{\partial p_i^2} = \frac{\partial^2 \pi_j}{\partial p_j^2} < -\frac{\partial^2 \pi_i}{\partial q_i \partial q_j} = -\frac{\partial^2 \pi_j}{\partial q_i \partial q_j}$ (stability condition strategic substitutes).

This information satisfies to derive the signs of the strategic, spillover, size and cost effect.

Proof of Proposition 4.10

First, note that (i) is a direct consequence of combining Proposition 4.8 with Proposition 4.9.

For (ii), observe that:

$$\widetilde{TS}_B - \widetilde{TS}_C = \frac{\gamma(a-c)^2}{\Phi_B^2 \Phi_C^2} F(\gamma,\beta,\theta),$$

where $\Phi_B = \gamma(1-\theta^2)(4-\theta^2)^2 - (2+\theta)^2(1-\theta^2)(1+\beta)$,

$\Phi_C = \gamma(4-\theta^2)^2 - (2-\theta)^2(1+\beta)$, and

$$F(\gamma,\beta,\theta) = \begin{array}{l}\left[\gamma(2+\theta)^2(1-\theta)^2(4-\theta^2)^2(3-2\theta)(1+\theta) - 2(2+\theta)^4(1-\theta)^4(1+\beta)\right]\Delta_C^2 \\ -\left[\gamma(2-\theta)^2(4-\theta^2)^2(3+\theta) - 2(2-\theta)^4(1+\beta)\right]\Delta_B^2\end{array}.$$

Again, the related function $G(\gamma,\beta,\theta) = F(\gamma,\beta,\theta)\Big/\left(\gamma\theta^2(4-\theta^2)^2\right)$ is considered. It follows that $sign\left(\widetilde{TS}_B - \widetilde{TS}_C\right) = sign\left(G(\gamma,\beta,\theta)\right)$.

Note that $G(\gamma,\beta,\theta) = \gamma^2 g_1 + \gamma g_2 + g_3$,

where $g_1 = (4-\theta^2)^4(1-\theta)^2(1+\theta)(4-2\theta-\theta^2)$,

$g_2 = 2(1+\beta)(4-\theta^2)^2(-16+32\theta-8\theta^2-20\theta^3+15\theta^4-3\theta^5+\theta^6-\theta^7)$, and

$g_3 = (1+\beta)^2(2+\theta)^2(1-\theta)^2(2-\theta)^2(4-2\theta+\theta^2-\theta^3)$.

Then, note that $G(\gamma,\beta,\theta)$ is strictly convex in γ as $\partial^2 G(\gamma,\beta,\theta)/\partial\gamma^2 = 2g_1 > 0$ (indeed: $\min_{\{\theta\}} g_1 = \lim_{\theta\to 1} g_1 = 0$). Moreover, $g_2^2 - 4g_1 g_3 > 0 \;\; \forall\; \theta \in]0,1[$. Hence, given any $\theta \in]0,1[$, there are two real solutions to $G(\gamma,\beta,\theta) = 0$, particular:

$$\bar{\gamma}_1(\theta) = \frac{-g_1 - \sqrt{g_2^2 - 4g_1 g_3}}{2g_1}, \text{ and } \quad \bar{\gamma}_2(\theta) = \frac{-g_1 + \sqrt{g_2^2 - 4g_1 g_3}}{2g_1}.$$

Only the larger root needs to be considered as

$$\min_{\{\theta,\beta\}}\left\{\gamma^* - \bar{\gamma}_1(\theta)\right\} = \lim_{\theta\to 0}\left\{\gamma^* - \bar{\gamma}_1(\theta)\right\}\Big|_{\beta=1} = 0,$$

where γ* is the threshold value induced by R2. Label this larger root $\bar{\gamma}(\theta)$. Then observe that $\min_{\{\theta,\beta\}}\left\{\partial\bar{\gamma}(\theta)/\partial\beta\right\} = \lim_{\theta\to 0}\partial\bar{\gamma}(\theta)/\partial\beta\Big|_{\beta=0.5} = 0.25$. This gives rise to the different lines as drawn in Figure 4.4 for different values of β. Obviously, for any $\gamma < \bar{\gamma}(\theta)$ we are in situation (i) while situation (ii) emerges for any $\gamma > \bar{\gamma}(\theta)$. The rest of the proof then follows.

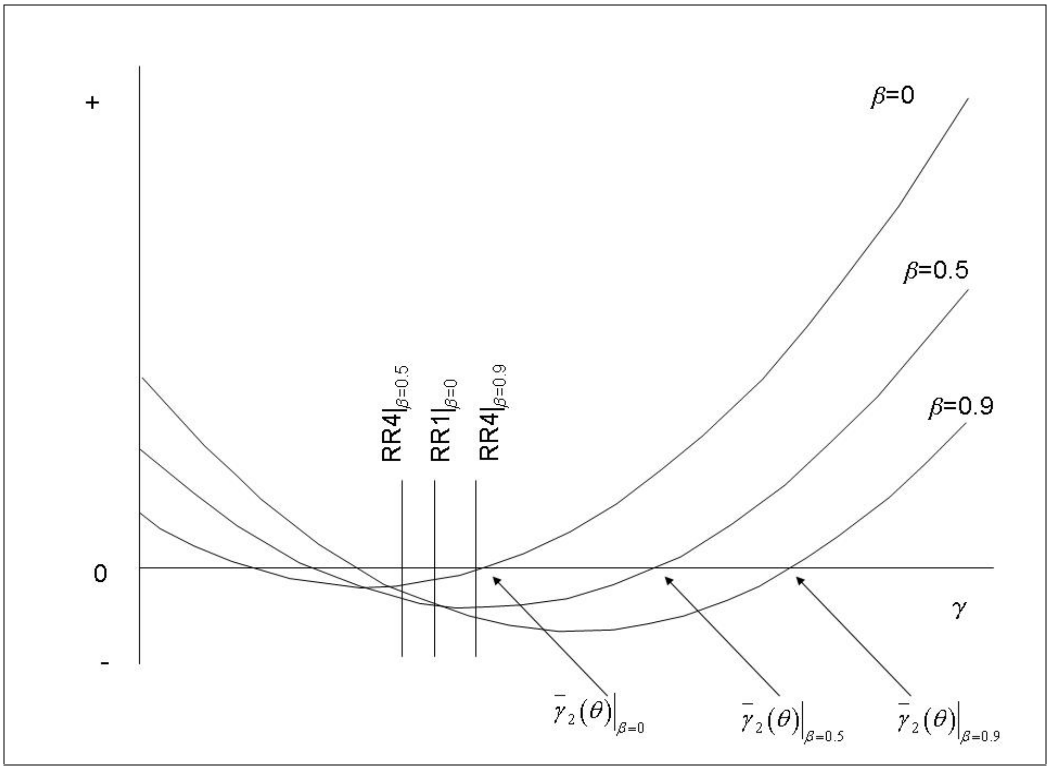

Figure 4.4. $G(\gamma,\beta,\theta)$ for different levels of R&D input spillovers: a=100, c=70 and θ=0.9.

5. General Conclusion

In this thesis, the role played by technological spillovers in firms' decisions to invest in R&D has been explored in three related studies. In the first two studies, attention has explicitly been devoted to the impact of spillovers on the comparison of efforts of leading and following firms. More insights into the process of technological leapfrogging or leadership persistence have been obtained. The last study has shed more light on the impact of competition intensity on R&D investment incentives.

In the first study, the impact of market leadership on innovative incentives has been analyzed in a static four stage strategic investment model. More specifically, an industry with (persistent) market leaders (e.g. Intel) and market followers is analyzed and it is assumed that the market leaders decide upon their R&D investments before the market followers. Furthermore, leaders and followers are allowed to cooperate in R&D. The cost-reducing R&D investments are accompanied by either symmetric or asymmetric technological spillovers.

Firstly, the findings of this study contribute to a better understanding of the impact of knowledge spillovers on R&D incentives when sequential moves are taken into account. Some remarkable differences with the familiar two stage models are detected. Indeed, when spillovers are symmetric, an increase in the spillover does not necessarily increase investments of cooperating leaders and cooperating followers in an R&D cartel. After all, cooperating leaders' investments are in general discouraged by an increase in the spillover, due to the negative impact on their investments, resulting from the leakage of knowledge to the followers. Only in the rare case in which more than half of the industry's firms would be a leader, their R&D investments would increase in the symmetric spillover when they would cooperate in an R&D cartel. Moreover, R&D cartelized followers' investments can also decrease in the symmetric spillover.

Secondly, further contributions to the Schumpeterian debate are provided by looking at the role played by spillovers in the comparison of R&D investments of leaders and followers. It is shown that this comparison and, hence, the technological leapfrogging opportunities for followers, depend to a large extent on the free riding opportunities of followers on the efforts of the leaders. In other words, the spillover from the leaders to the followers is a crucial factor in the process of technological leapfrogging; the larger is the spillover from the leaders to the followers, the more likely it is that technological leapfrogging takes place. Consequently, the leaders want to minimize and the followers want to maximize the spillovers from the former to the latter.

For example, labour mobility is often argued to be an important source of knowledge spillovers (see for example Geroski, 1995). Consequently, leaders' ability to prevent employees from leaving and follower's capabilities to attract leaders' R&D personnel will tend to play a major role in the process of technological leapfrogging. In the end, this may result in bidding for R&D personnel (Gersbach and Schmutzler, 2003).

Our study moreover illustrates that also R&D cooperation may play an important role in the process of technological leapfrogging. On the one hand, leaders may deter technological leapfrogging by combining R&D forces, provided that the cooperating leaders increase knowledge sharing. On the other hand, R&D cooperation among followers may stimulate technological leapfrogging, on the condition that they fully share knowledge. R&D cooperation is thus always effective for leaders in reducing leapfrogging opportunities when they form an RJV cartel. Analogously, an RJV cartel among followers may always increase leapfrogging opportunities. It could thus be argued that both leaders and followers would like to cooperate in an RJV cartel as it strengthens their competitive position. Unfortunately, the question concerning the impact of R&D cooperation of both leaders and followers on the process of technological leapfrogging remains unanswered here.

Important insights are furthermore gathered into the effectiveness of R&D cooperation on firms' R&D investments and welfare. In line with previous studies, such as the seminal work of d'Aspremont and Jacquemin (1988) and Kamien et al. (1992), the comparison of R&D competitive and R&D cooperative investments of leaders and followers is driven by critical spillover levels. Put differently, R&D cooperation among leaders (followers) in an R&D cartel only results in higher R&D investments, compared to R&D competition, when the spillover is sufficiently large. Important to mention is that these critical spillovers are not necessarily the same as in the traditional two stage games with simultaneous moves. Indeed, the critical spillovers for the leaders can be relatively high, especially when there are only a few leaders.

The study moreover shows that the same critical spillovers determine the social desirability of R&D cooperation. Indeed, the findings reveal that R&D cooperation is only beneficial for society when it results in higher R&D investments of the cooperating firms. In this regard, it has been pointed out that government intervention critically hinges on the industry structure, i.e. the number of leaders and followers. When there are a lot of leading firms, society is best off when these leading firms cooperate in an RJV cartel. However, it is most common that only a few firms dominate the market. In that case, it is best to favour R&D cooperation of only the small following firms.

Whereas the model of the first study is static, as investments occur only once, a more dynamic model is analyzed in the second study. In this model, firms compete for the market by investing continuously in R&D. More specifically, one incumbent and one or more entrants race to be the first to innovate (a new product or a new technology) and the winner of the race is rewarded with a prize, namely a patent. The R&D process is furthermore characterized by uncertainty as increasing investments only increase the probability of winning the race. However, an important assumption in the study here is that patents may not always work as prescribed by theory. Consequently, the winner of the race may not always be able to appropriate the full value of the innovation, as, due to imperfect patents, losers of the race may also reap some of the fruits of the innovation. Finally, both settings with exogenous entry (given number of entrants) and free entry (endogenously determined number of entrants) are looked at.

After all, previous literature demonstrates that the distinction between exogenous and endogenous entry plays an important role in the process of technological leapfrogging or leadership persistence in patent races with winner-takes-all. Indeed, with exogenous entry, the incumbent always invests less than the entrant when there is winner-takes-all by which leadership persistence is more likely than technological leapfrogging (Reinganum, 1985). With endogenous entry and winner-takes-all, Etro

(2004) finds that the incumbent always invests more than the entrants and thus, leadership persistence tends to be the rule.

The findings of our study illustrate that, besides the distinction between exogenous and endogenous entry, reward sharing plays also an important role in the process of technological leapfrogging or leadership persistence. With exogenous entry, it is possible that the incumbent invests more than the entrants. More specifically, when entrants commit to sharing rewards with other entrants, the incumbent invests more than the entrants when the reward sharing is sufficiently large. Thus, with exogenous entry, leadership persistence is in some cases more likely than technological leapfrogging.

When there is endogenous entry, the incumbent generally invests more than the entrants. However, when a winning incumbent has to share the prize of the innovation with losing entrants, the latter tend to invest more than the former when the reward sharing is sufficiently large and thus, technological leapfrogging is not impossible in patent races with endogenous entry.

It has furthermore been demonstrated that both the incumbent and the entrants overinvest in R&D compared to the socially optimal expenditures on R&D. A possible policy in order to reduce the incumbent's and the entrants' investments might be the taxation of R&D. Remark that the optimal taxation will (probably) depend on the level of reward sharing, which in turn differs across industries.

The third and last study of this thesis deals with the comparison of the economic performance of Cournot and Bertrand competition when the market competition stage is preceded by a stage of competitive or cooperative investments in cost-reducing R&D in the presence of input spillovers. This study closely relates to that of Qiu (1997). However, there are two important differences. Firstly, input spillovers are considered here, whereas Qiu (1997) assumes output spillovers. Secondly, Qiu (1997) only analyzes R&D competition while in this study both R&D competition and R&D cooperation are looked at.

The study firstly shows that, both with R&D competition and R&D cooperation, duopolists invest more in R&D when they compete with quantities (Cournot) than with prices (Bertrand). In other words, less intense competition modes (Cournot) can yield larger R&D investments compared to more intense modes of competition (Bertrand). The reasoning behind this is that cost reductions are transferred much more to consumers under Bertrand competition than under Cournot competition, by which R&D incentives are lower under the former than under the latter competition mode. It has furthermore been indicated that the difference between R&D investments under Cournot and Bertrand is larger, the less products are differentiated, the larger the spillover is and the more efficient the R&D process is.

These higher investments under Cournot compared to Bertrand competition are not without consequences for the comparison of consumer surplus and welfare under these two competition modes. Indeed, when spillovers tend to be larger, products are not that differentiated and the R&D process is efficient, the R&D investments and concomitant cost-reductions with Cournot competition can be that much higher than with Bertrand competition by which prices can be lower under the former competition mode than under the latter. Thus, consumers can be better off with Cournot than with Bertrand competition. Keeping in mind that producer surplus is always larger under Cournot than under Bertrand competition, it is then easy to understand that total surplus, as the sum of consumer and producer surplus, can also be higher with quantity than with price competition.

This study illustrates that the effectiveness of R&D policy instruments might depend on the competition intensity in industries. After all, less intense competition modes might result in larger R&D efforts than more intense competition modes. As there is, with both competition modes, underinvestment in R&D, R&D subsidies should probably be higher in markets with Bertrand competition.

All in all, the findings of this thesis clearly show that appropriability problems can influence the comparison between leaders' and followers' R&D investments dramatically. The last study contributes to a better understanding of the impact of market structure on firms' R&D incentives.

Before closing, it might be interesting to point to some possibilities for further research. It would be interesting to analyze how technological leapfrogging opportunities would be affected when both leaders and followers would cooperate in R&D in the setting of the first study. Moreover, in some industries, for example in the pharmaceutical biotechnology industry, it is not uncommon that R&D cooperation takes place between large and small firms (see for example Roijakkers and Hagedoorn, 2006). Therefore, the model could also be used to evaluate the impact of R&D cooperatives between large and small firms. While doing so, more asymmetry between leaders and followers could be taken into account by assuming lower ex ante unit costs and/or a more efficient R&D process for leaders.

Furthermore, although the sequence of play in the first study can be observed in some industries, it is however also possible that, in other industries, other sequences of play prevail. For example, it could well be the case that market leaders prefer an imitative strategy. It would therefore be worth the effort to endogenize the innovator and imitator roles, given the Stackelberg scenario on the output market.

The second study could be extended to the case in which entrants coordinate their R&D strategies (by maximizing joint profits). After all, we know from the first study that R&D cooperation among followers may enhance technological leapfrogging opportunities of followers. By introducing an R&D cartel among entrants, it would then be possible to evaluate whether technological leapfrogging is also more likely in settings in which there is dynamic competition for the market. A logical next step is then to consider patent races with two or more incumbents and R&D cartelization between these incumbents. Introducing R&D cartelization in patent races may also be interesting from the social planner's perspective as it may indicate whether R&D cooperation yields higher or lower investments compared to R&D competition. Moreover, other reward sharing scenarios could be analyzed. After all, it may be clear that the reward sharing scenarios analyzed in this study are not the only possible scenarios.

The third study could firstly be extended to the case to an industry with *n* firms. The impact of the number of firms on R&D investments in Cournot and Bertrand competition could then be compared with the findings of Aghion et al. (2006) who claim that there is an inverted U-shape relation between the level of competition and the innovative activities of firms. Finally, it would be interesting to compare R&D investments, profits and welfare when firms decide sequentially on output and prices.

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