Abstract

This paper investigates strategic R&D under-investment for purpose of entrance deterrence when there are knowledge spillovers. Therefore a two-periods, two-firms model is set up under the assumptions of a knowledge adoption lag of one period and ex-ante identical firms. The firms can either move early or late. In case of simultaneous entry, the firms invest in unit cost reducing R&D and afterwards compete in the market in a Cournot game. Sequential entry results in a Stackelberg game in R&D investment and a monopoly in the first period and if the second firm follows a Cournot game in the second market period. In this case, the first-moving firm can blockade, deter, or accommodate the follower's entry according to the terminology of Tirole's Stackelberg-Spence-Dixit model. The results confirm that R&D under-investment to deter a follower's entry is an option for an early moving firm. Depending on the magnitude of the fixed entry cost, the under-investment is in contrast to the Stackelberg R&D amount or the monopoly investment. But since a potential second-moving firm knows about the deterrence possibility, it will avoid this situation by also moving early.

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1 Introduction

R&D with spillovers is considered extensively in the literature of industrial organization. So far, studying cooperative and noncooperative behavior is predominant. The focus thereby is on the market failure that arises since R&D investing firms do not take the positive external effect of leaking knowledge into account. In contrast, firms that intentionally reduce the R&D investments are only scarcely investigated. With this paper one important research gap is filled by considering strategic under-investment with entry deterrence motive. More precisely a model under the assumptions of ex-ante identical firms and a R&D knowledge adoption lag of one period is set up.

The main interest is to analyze if entrance deterrence by R&D under-investment is a strategic option for an incumbent firm. To get more information about the relevance of this setup, it is integrated in a static game of complete information. In a precompetitive stage, two ex-ante identical firms can decide to invest and enter the market in the first or in the second period. Afterwards those decisions become common knowledge and three different games can arise: Firstly, both firms move early. They invest in unit cost reducing R&D prior to the first market period and then compete in a Cournot game. With a disclosure lag of one period, parts of the R&D outcome spill over and hence also lower the unit costs of the rival in the second market period. Secondly, the firms simultaneously enter the market entry in the second period, such that no spillovers occur. The firms invest prior to period two and then also compete in a Cournot game. Having both cases in one paper allows a revealing comparison of the effect of R&D spillover on investments, profit and welfare. Nevertheless, the focus is on the third game with sequential entry; a Stackelberg game in R&D accrues: One firm is already active in period one, where it has a temporary monopoly. The second firm follows in period two if it can gain a positive profit. Knowing that, the incumbent tries to keep the second-mover out of the market by strategic investment according to the terminology of Tirole's (1994) Stackelberg-Spence-Dixit model. Dependent on the fixed entry cost, the incumbent plays blockaded entry, entry deterrence or accommodated entry.

To highlight the practical relevance, the model is embedded in the environment of energy generation. More precisely, the fossil sector is taken as well established and hence only the renewable sector is constructed. In doing so, the paper provides a contribution to the debate if there is a need to help building up this sector[1]. In fact, many countries introduced support schemes to subsidize renewable energies in the electricity sector (IPCC 2014). However, support schemes are only economically justified in the presence of market failures, whereas carbon externalities cannot be directly internalized by renewable support schemes and are often already taken into account by other instruments (e.g. the EU emission trading system). In contrast, under-investment with the purpose of entry deterrence might be a case for an additional support mechanism for renewable energies.

To ascertain under-investment with an entry deterrence motive, the paper is organized as follows. Section 2, reviews the relevant literature on R&D investments in the presence of spillovers (2.1) and entrance deterrence (2.2). In section 3, the model is set up, where firstly the monopoly and then the basic duopoly case is considered. The basic game consists of two simultaneous entry games and one with sequential entry. Applying the Stackelberg-Spence-Dixit interpretation then provides a new strategic option for the first-mover of the latter (3.4). Section 4 gives a detailed explanation of the model and its interpretation on basis of a numerical example as well as a game theoretical analysis and policy implications. The last section concludes.

2 Literature review

In this section the relevant literature is presented. The first chapter gives an overview of relevant papers regarding R&D investment under spillover. The second chapter reviews the literature regarding strategic investment with entrance deterrence motive.

[1] For example, Edenhofer et al. (2013) review in which cases a certain share of renewable energy should be a political aim.

2.1 R&D investment under spillover

A large number of papers on R&D investment under spillover has been published over the last decades. Section 2.1.1 gives an overview of the main literature in the different research fields and the relevant publications for this paper. The two most important classifications are "Strategic R&D under-investment" and "R&D investment in the presence of a potential entrant" which is why they are presented separately in section 2.1.2 and 2.1.3.

2.1.1 Basic literature

The main literature on R&D under the presence of spillovers is based on the models of D'Aspremont and Jacquemin (1988, 1990) and Kamien et al. (1992). Both consider a two-stage duopoly game. In the first stage, firms decide about their investing decision to lower the initial unit costs. A part of this R&D spills over to the rival as an external effect and lowers its unit production cost. In the second stage, the firms compete in the product market. In D'Aspremont and Jacquemin, the level of R&D investment and amount of production is determined for three different cases: Monopoly, cooperative, and noncooperative behavior. They found that the investments increase towards an optimal level when firms cooperate in R&D, and therewith also the amount of production. In other words, for the noncooperative behavior, a case of under-investment is shown. A detailed explanation for the reason of the under-investment in this model can be found in section 2.1.2.

Kamien et al. (1992) proceed in a similar way. They construct four different scenarios: First, R&D competition, where firms invest unilaterally. Second, R&D cartelization, where firms coordinate their R&D expenditures but still compete in the product market. Thirdly, research joint venture competition, which is defined as unilateral R&D expenditures but with fully shared R&D results (perfect spillover) and fourthly, a research joint venture cartel, where all firms together optimize the industry profit. They show that the competitive research joint venture induces under-investment compared to R&D competition, due to a free-rider problem. In contrast, the research

joint venture cartel is welfare superior in most cases. In both papers underinvestment can be found, although the assumptions are not identical. The main difference is that in D'Aspremont and Jacquemin parts of the R&D output spills over to the rival, whereas Kamien et al. assume that the external effect is driven by the R&D inputs. The latter approach was pioneered by Ruff (1969). He considered an infinite-horizon model with firms choosing R&D expenditures under spillovers, and compared the noncooperative solution with the social optimum. Spence (1984) and Katz (1986) followed the procedure of optimizing over R&D efforts. Kamien et al. rediscovered the approach after D'Aspremont and Jacquemin published their model and therewith a large number of publications based on either of the two models ensued. However, Amir (2000) shows that these two R&D processes can be equalized under certain conditions.
The present model is based on D'Aspremont and Jacquemin since firms with entry deterrence motive are interested in the realized improvement, that partly benefits the rival and not the money spent on the R&D program. Nevertheless, Tesoriere (2008) uses the same R&D technology as D'Aspremont and Jacquemin but is not optimizing via the output but applies a transformation to get the R&D production function and optimizes over the input. Thus we use the terms R&D investment and output equally as both can easily be converted into each other.

After D'Aspremont and Jacquemin, a large literature based on their model has emerged[2]. Starting from the two-stage, two-firms approach, the papers analyze different variations or attempt to provide alternative explanations or policy recommendations for the existing models. Among those, papers regarding the evaluation of different kinds of cooperative R&D agreements, especially research joint ventures, relative to noncooperative R&D are predominant[3]. For this paper, Erkal and Piccinin (2010) and Bandyopadhyay

[2]Henriques (1990), De Bondt and Veugelers (1991), Suzumura (1992), Vonortas (1994), Poyago-Theotoky (1995), De Bondt (1996), Leahy and Neary (1997), Hinloopen (1997, 2000), Cellini and Lambertini (2009) and Hinloopen and Vandekerckhove (2009) to name but a few.

[3]Some of them are Suzumura (1992), Ziss (1994), Poyago-Theotoky (1995), Amir and

and Mukherjee (2014) are of high interest, since both consider the effect of entering firms on the incentive to cooperate. The topic of strategic behavior in the presence of a potential entrant is described in detail in section 2.1.3.

Others like De Bondt and Henriques (1995) include asymmetries such that the firms differ in their learning or absorption capacities[4], by adding a pre-development basic research state to the R&D and production stage. Further studies mainly focus on the spillovers (e.g. endogenous spillovers like in Katsoulacos and Ulph (1998)) or especially the correlated spillover parameter[5]. The study of Tesoriere (2008) differs from others because of the assumption of endogenous asymmetric firms and the specification that the spillovers only flow from the first-mover to the follower[6]. In a game theoretic approach, he looks for a subgame perfect Nash equilibrium in a duopoly model based on D'Aspremont and Jaquemin[7]. Both firms decide in a precompetitive stage to move early or late. After that, the result is common knowledge and either a simultaneous or a sequential game starts. If both firms decide to move early or late, the firms simultaneously invest in R&D and then compete in the product market. In this case, no spillovers occur, since he assumes that the firms need to observe the R&D results before they can imitate them. The second game is played if one firm wants to move early and the other late. Now three stages arise: In the first stage, the early moving firm makes its investment decision and becomes the Stackelberg leader in R&D. In the second stage, the late moving firm invests in R&D by observing the rivals investment. Due to the sequential R&D investment, the follower can imitate the first-mover and gains knowledge spillovers. In the third stage, Cournot competition takes place. Hence, the first-mover has the Stackelberg leader-

Wooders (1999, 2000), Amir (2000), Miyagiwa and Ohno (2002), and Suetens (2005).

[4]For more on absorptive capacity see Grünfeld (2003). Ishida et al. (2011) split the firms in efficient low-cost firms and less efficient high-cost firms.

[5]Highly relevant cornerstone papers in this field are Reinganum (1981) and Katz (1986).

[6]Among others, Amir and Wooders (1999) considered also one-way spillovers in a pure simultaneous move game, whereas the flow goes from the more R&D intensive firm to the other.

[7]Another paper that applies game theory on D'Aspremont and Jaquemin (1988) is, for instance, Amir et al. (2011). They find that the firms in the duopoly are engaged in a prisoner's dilemma when spillover effects are low.

ship in R&D, whereas the follower gains from spillovers. Intuitively, small spillovers make the leader position more attractive, whereas in case of large spillovers the firms would favor to be the follower. The two firms only decide to play the sequential game, if both positions yield higher profits than simultaneous R&D investments. Otherwise, at least one firm can do better by shifting to the same timing as the rival which than results in a simultaneous game. Tesoriere finds that there is no spillover rate such that the sequential game Pareto dominates the simultaneous game. As a consequence, the latter is the only subgame perfect Nash equilibrium and thus no spillovers emerge. Tesoriere (2008) is highly relevant for the current paper. First of all, the spillovers also occur after observation and imitation, which takes one period here. But since this model consists of two periods, they also arise if both firms enter the market in period one. For simultaneous entry in period two the spillovers are zero. Furthermore, the concept of a precompetitive stage is applied to schedule the entry order (section 3.3.1).

Another relevant classification concerns the level of information. Elberfeld and Nti (2004) and Zhang et al. (2014) add ex-ante uncertainty about the R&D output and investigate how the investment strategy changes.[8] As one possible outcome they name under-investment compared to full information. More on that can be found in section 2.1.2.

An evaluation of the R&D intensity can be found in almost all papers on this subject. Depending on assumptions regarding the structure of the production function and costs, spillovers, industrial interconnection between firms or degree of competition, over- or under-investment occurs. The main interest of the present paper is to show if entrance deterrence by R&D under-investment is feasible. Therefore, the next section gives an overview of the literature dealing with R&D under-investment.

[8]Other papers that included uncertainty in their R&D models are for example Reinganum (1984), Miyagiwa and Ohno (2002).

2.1.2 Strategic R&D under-investment

In the majority of cases, knowledge spillovers lower the incentive to invest in R&D compared to full appropriation, since the rival can benefit from them too, without incurring costs. Thus, the investing firm starts acting strategically as soon as spillovers occur. In this section, relevant publications regarding this behavior are presented.

D'Aspremont and Jacquemin (1988) find differences in the amount of R&D investment between three different cases of noncooperative and cooperative R&D optimization. In a two-stage, two-firms model, firms invest in R&D to lower the unit production costs, whereas parts of that spill over to the rival, before both compete in the product market. In the first case, firms act noncooperatively in both stages. After that they look on a R&D cooperation, where firms maximize the joint profits via R&D investments but still compete in the product market. The authors expected a reduction of R&D because of less duplication of costs but found that the levels of R&D increase, especially for large spillover. The same holds for the industry production and the profits. For large spillovers, the R&D cooperation increases R&D expenditures and the produced quantities, such that in the noncooperative game an inefficient under-investment occurs. The third case represents a collusion, which can be treated like a monopoly since firms fully cooperate in both stages. The monopolist invests more in R&D than the cooperation since it can achieve more of the surplus created by the R&D due to less competition in the product market, indicating that the produced quantity is less than under R&D cooperation. The comparison of production and R&D output between the noncooperative and the two cooperative solutions strongly depends on the value of the spillover parameter. Generally, for large spillovers the R&D amount in the monopoly is closest to the social optimum, but in terms of produced quantity the R&D cooperation is closest. For small spillovers the results change but the monopoly R&D stays the highest of the three cases. If firms do not coordinate their R&D expenditures, under-investment emerges since the positive external effect of the investments is not internalized. As the current paper uses crucial parts of the basic structure of D'Aspremont and Jacquemin, like the R&D process and the spillover flow, the firms will under-invest likewise as soon as they create positive spillovers for the rival. This is not the strategic under-investment we are interested in here but rather under-investment regarding the entrance deterrence motive of an incumbent firm.

Another reason for under-investment can be uncertainty. For example, Zhang et al. (2014) investigate how spillovers change the investment decision in the presence of uncertain R&D outcomes and find under-investment as one outcome. By setting up a two-stage model, where active firms first decide whether to adopt a new technology that lowers expected marginal costs or not and than compete together with inactive firms on the product market (where the latter do not absorb spillovers but active firms does), they find that increasing information spillovers lower the firms' incentive to innovate compared to the socially optimum[9]. However, there is no uncertainty in the current model. The important aspect is that the firms are not ex-ante in the market unlike in Zhang et al. (2014), such that another reason for under-investment occurs: A potential entrant.

2.1.3 R&D investment in the presence of a potential entrant

In a newer field of R&D with spillovers, researchers investigate how potential entrants affect the investment strategy of incumbent firms. Since the prevailing literature on R&D with spillovers regards research cooperations, also quite a few papers deal with the effect of entry on the intention to cooperate in R&D, which are described here. The main argument is that a cooperation increases or decreases the investments and therewith the spillovers, such that one motive is under-investment again. Besides, some of the papers already use the same terminology as Tirole (1994) in the Stackelberg-Spence-Dixit model, which is introduced in the next section and core of the current paper.

[9]In an early publication, Reinganum (1984) shows a similar result. He finds that under stochastic R&D success, lowering the assumption of a perfect patent leads to under-investment.

In other words, the reason to form a R&D cooperation is in the entrance deterrence motive. Section 2.2.2 gives a closer look on literature focusing on entrance deterrence by R&D under-investment. Some of the papers presented here would also fit in this classification but since their focus is on the change in cooperation strategies, they are ranged here. Nevertheless, they are highly relevant for the current paper.

The first paper that deals with a R&D model in presence of potential entrants comes from Erkal and Piccinin (2010). They find that allowing for free entry in a model with stochastic R&D "introduces new strategic, investment and welfare implications of cooperative R&D" (Erkal and Piccinin, 2010, p. 75). Following the literature, they set up different cases of cooperative and non-cooperative behavior. Under the presence of potential entrants, R&D cartels (firms choose their R&D levels in order to maximize the joint profit but do not share the generated knowledge) found to be never profitable compared to R&D competition, which is on the contrary to models with a fixed numbers of firms. Since profitability in case of research joint venture cartels (same as a R&D cartel but with shared knowledge) is only achieved for small cartels, the authors derive that it is necessary to share the generated knowledge to successfully run cooperative R&D arrangements under free entry.

O'Sullivan (2013) is closely related to Erkal and Piccinin (2010). In his model, the incumbent firms can invest prior to an potential entrant, either individually or in a research joint venture. This allows for blockaded entry, entry deterrence, or accommodation through the R&D behavior. O'Sullivan is mainly interested if in the case of R&D competition and accommodated entry, the formation of a research joint venture can deter entry, which depends on the spillover rate and the firms' R&D efficiency. However, if spillover rates are sufficiently low, a research joint venture can deter the entry.

Furthermore, Bandyopadhyay and Mukherjee (2014) find in a very recent publication that the presence of a potential entrant plays a decisive role in determining R&D organizations. Under the threat of entry the incentive to cooperate in R&D increases. The potential entrant can only enter the market if there is sufficient knowledge spillover. The more of the incumbent firms are using the full version of the new technology, the higher is the benefit of the potential entrant. In the model, each of the firms in the market face a menu of projects, only one of which can be successful and then generates marginal production costs of zero, whereas success in R&D is uncertain. Before adding a potential entrant, Bandyopadhyay and Mukherjee introduce the plain noncooperative and cooperative R&D strategies. In a noncooperative approach, each firm can only run one project. But if one firm succeeds, parts of the generated knowledge spill over to the unsuccessful firms. In case of cooperative R&D, knowledge and risk a shared equally due to a research joint venture. Through the therewith decreasing costs, the competition in the product market increases, but firms' overall profit is higher compared to the noncooperative approach since the positive effects dominate. Now a third firm can enter the market. It is non-innovating but can also profit from spillovers, whereas knowledge spillovers to the unsuccessful innovating firm is higher so it will enter also if any other firm is successful while the non-innovating firm may not find entry always profitable. Based on this, they consider several cases for different constellations of knowledge spillovers and marginal cost differences. Firstly, entry occurs when only one innovating firm has full access to the new technology. From this follows that entry is deterred if both incumbent investing firms have access to the new technology and unilateral success under noncooperative R&D induces entry. This increases the possibility of entry and therewith the incentive for cooperative R&D compared to the situation with no entry by another firm. Second, entry only occurs when both innovating firms have full access to the new technology. Thus, a potential entrant reduces the incentive to cooperate in R&D and therewith the total probability of success in R&D, because the incumbent firms' gain from higher product market profit through entry deterrence, which outweighs the loss from lower probability of success in R&D. A case of entry deterrence by under-investment arises. In the third constellation, entry occurs whenever at least one innovating firm has full access to the new technology. Now entry may increase or decrease the incentive to cooperate in R&D depending on the extent of spillover, the marginal cost differences and the probability of success. However, Bandyopadhyay and Mukherjee are primarily interested in how the incentive to cooperate changes if there is a potential entrant and not the deterrence motive itself, which is the focus of the present paper. But it is interesting that the current model endogenously leads to the important assumption of Bandyopadhyay and Mukherjee: They used the fact that the entrant needs knowledge spillovers such that market entering is profitable to construct the deterrence possibility. Here the same holds for a specific magnitude of the fixed entry cost as shown later (e.g. section 4.2.2).

2.2 Strategic investment with entrance deterrence motive

Various fields of strategic investments exist, for example, capacity investments or R&D in product quality or costs[10]. What they all have in common is that firms try to maximize profits by inciting an actual or potential rival to a certain action (De Bondt and Veugelers, 1991). Here we are particularly interested in strategic investments with entrance deterrence motive[11] like the limit pricing strategy of a monopolist, where she sells the products at a lower price than usually to discourage potential competitors. By that she makes less profit compared to a standard monopoly but still more than under oligopoly or even perfect competition. The strategy only works if the threat is credible. Otherwise, the entrants know that as soon as they enter the market the monopolist's best response changes and the limit price cannot deter entry. In the literature, a wide ranch of approaches on this can be found. One of them, the Stackelberg-Spence-Dixit model by Tirole (1994) is presented in the first part of this section, since it builds the basis of the strategic investment in this paper. The second part follows with an outline of the existing literature on entrance deterrence by under-investment.

[10]One of the first publications on strategic R&D comes from Ruff (1969). Others like Dasgupta and Stiglitz (1980) and Spence (1984) followed. See Tirole (1994) for a wide range of strategic investment activities.

[11]The literature on entry prevention starts with Bain (1956). See McAfee et al. (2014) for a chronological overview, including the different definitions of entry barrier.

2.2.1 Stackelberg-Spence-Dixit model

Unlike the here investigated strategic investment in unit cost reducing R&D, Tirole's (1994) Stackelberg-Spence-Dixit model (based on Stackelberg (1934), Spence (1977, 1979) and Dixit (1979)), deals with strategic investment in capacity. The key of the model is the commitment effect of the barrier to entry. Tirole assumes two temporal asymmetric firms. Hence, for example one firm receives the technology earlier, such that this firm becomes the first-mover. This incumbent firm builds up capacity, which than can be seen as sunk costs and thus constitutes the necessary credible threat indicating that it will supply a higher amount of the good than under Stackelberg or Cournot competition. Thereby, three stages can be distinguished: Firstly, the incumbent firm acts as a monopolist instead of a Stackelberg leader and builds up a capacity equal to its monopoly quantity. If it is already big enough to keep the potential entrant out of the market (due to a fixed entrance fee), the entry is called "blockaded". If it is not big enough yet, the incumbent can build up a higher capacity such that the entrant does not enter. This is then called "entrance deterrence". As a third course of action, the incumbent can play "accommodated entry", which occurs if it is too costly to build up the entry deterrence capacity and thus profit is higher if it lets the rival into the market. Nevertheless, the first-mover tries to affect the follower's behavior with its earlier investment decision[12]. Several papers are build on a earlier publication of the Stackelberg-Spence-Dixit model, for instance Schmalensee (1981). Instead of a fixed entrance cost, he assumes that the firms cannot produce below a minimum level of output.[13] In this paper, the commitment effect is achieved by R&D expenditures that are sunk and cannot be changed once they are invested. On basis of this, the

[12] In this regard, Tirole also states a possible circumstance in that under-investment arises: If there are several incumbents instead of only one, entry deterrence becomes a public good. Once the first incumbent invests in capital to deter a potential entrant, all the other incumbents also benefit. Under-investment occurs since every incumbent would like to keep the other firm out of the market but no one wants to incur the associated costs. A more recent paper on this topic with a good literature review is Kovenock and Roy (2005).

[13] Other modifications of the model can be found in Gilbert and Vives (1986) and Waldman (1987).

Stackelberg-Spence-Dixit interpretation of Tirole is applied. In section 3.4, Tirole's model is adapted to the current one. A detailed description follows in section 4.2. The next section gives a summary of an earlier publication that used a similar approach and gives a comparison with this model to reveal the need for research.

2.2.2 Entrance deterrence by R&D under-investment

The first moving firm in the present model has two opposed effects based on the R&D investments. The first one is equivalent to the described limit pricing strategy with the difference that the price is not just lower because of a higher supply but decreased unit costs due to more R&D. Since the expenditures are sunk, this would be a credible threat such that the incumbent can possibly deter the potential entry by over-investment, which is not examined in this paper. The second effect is spillover-induced: As there are knowledge spillovers that lower the rivals unit costs, the incumbent firm tries to reduce its R&D output such that the entrant can not profit enough from the positive externality to cover its fixed entrance costs and thus stays out of the market. It depends on the specific model and the magnitude of the spillover parameter, if potential entry discourages or enhances firm's R&D investment. In chapter 3, the model is presented without fixing a value for the spillover parameter. After that the spillover parameter is set equal to one (which implicates perfect spillovers) to test if the incumbent firm has the ability to deter the followers entry by playing "limit under-investment" as an equivalent to “limit pricing”. Since the R&D expenditures are sunk and cannot be increased later on, they are credible and hence fulfill the commitment effect. Only one paper covered this approach so far. A brief summary will be given in this section.

Rossell and Walker (1999) are looking on the incumbent's investment strategy under R&D spillovers when facing a potential entrant. The game consists of two stages. In the first stage the firms invest in cost reducing R&D in a Stackelberg order, with the incumbent firm as the leader and the entrant as the follower. In case of entry the follower faces a fixed entry cost. Afterwards both compete in the product market. Otherwise the incumbent firm behaves as a monopolist. Based on this structure, Rossell and Walker briefly examine the cases of blockaded entry, entry deterrence and accommodated entry. They not only find that under-investment can occur as a deterrence strategy, but even entry solicitation to benefit from the rivals R&D output. This means that the incumbent firm wants the competitor in the market since the unit cost reduction by knowledge spillovers compensate for the loss of the monopoly position. Solicitation could therefore be an option for large spillover and if the second movers R&D can immediately spill over to the incumbent firm. In contrast, the spillovers in the current model face an adoption lag of one period since empirical investigations found evidence on that. For example, Cohen et al. (2002) found that the average adoption lags for unpatented process innovations are 2.03 years in Japan and 3.37 in the U.S. In an earlier publication, Mansfield (1985) computed that in 59% of the relevant cases the recipient of the knowledge needs more than one year to obtain relevant information. Furthermore, the firms are ex-ante inhomogeneous, which is dropped here to get more insights in the arising market structures.

3 The Model

First of all the basic framework and relevant assumptions are presented. After that, the analysis starts with the monopoly case followed by the duopoly, where each possible game is analyzed separately, but the sequential game on which the Stackelberg-Spence-Dixit interpretation is applied to in most detail. An extensive interpretation of all results follows in the numerical example (section 4), whereas the focus of this chapter is on the description of the analytical modeling.

3.1 Basic framework

The demand side is given by the linear inverse market demand function $P(Q) = a - bQ$, where Q is the quantity, P is the price, and $a > 0$ is a constant. For simplicity, b is set equal to 1. To apply our example, by following an approach of Schmidt and Marschinski (2009), it can likewise be interpreted as the residual demand for renewable energy, where Q is the energy generated by the renewable energy sector, e.g. wind energy. Since two production periods and two firms are considered, the residual inverse demand in period $t = 1, 2$ is $P(Q_t) = a - Q_t$, where Q_t is the aggregate supply: $Q_t = q_{A,t} + q_{B,t}$ with $q_{i,t}$ is the output of firm $i (i = A, B)$ in period t. The two firms can enter the market in period one or two. If they do so, they have to spend the fixed market entry cost f. The fixed entry costs are the same, independently of entry happens in the first or the second period. Furthermore, before entering, they can invest in unit cost reducing R&D. Without R&D the production costs of the homogenous good $q_{i,t}$ are $c > 0$. To get the effect of decreasing returns to R&D expenditures, that is justified by, for instance, D'Aspremont and Jacquemin (1988) and Dasgupta (1986), the cost of R&D are assumed to be quadratic:

$$R_i = \frac{\gamma x_i^2}{2},$$

where x_i is the individual cost reduction of firm i and γ is a constant which when multiplied by x_i reflects the marginal cost of R&D investment. To get meaningful results, γ needs to be bigger than 1, as explained later. Generally it would be interesting to split the fixed cost such that a part of them can also decrease through R&D, but this is out of the scope of this paper. Here it is enough to interpret the fixed costs as necessary expenses that are not affected by R&D. By way of illustration, a wind turbine itself consists of a foundation, tower, blade and much more that every turbine needs independently of the engineering progress. Nevertheless, we will come back to that in the conclusion.

A part of the R&D output additively spills over to the other firm. However, spillovers only occur after a disclosure lag of one period, since it takes a while until the other firm exploits it. Due to that, there are no spillovers in the period of entrance in case of simultaneous investments[14]. If one firm enters the market in period one and the second in period two, the first-mover cannot benefit from the followers R&D investments whereas the follower instantly does. If, for example, both firms invest in R&D and enter the market in period one, the effective unit cost reductions are

$$K_{i,1} = x_i$$
$$K_{i,2} = x_i + \beta x_{-i},$$

where β is the spillover parameter that can lie in a range of $0 \leq \beta \leq 1$. A spillover parameter of 0 means no spillovers whereas a spillover rate of 1 reflects perfect spillovers[15]. In the latter case, the R&D output is a perfect substitute. Up to now, R&D investments are seen as process innovations that lower the unit costs. According to De Bondt and Veugelers (1991) and Bandyopadhyay and Mukherjee (2014) they can alternatively be interpreted as demand promoting. This can easily be used as an explanation why the firms that only invest in period one can gain from knowledge spillovers in period two without investing again.

Once the firms entered the market, they compete on the product market under the assumption of Cournot-Nash behavior. This also holds for the Stackelberg game in terms of R&D investments, which occurs in case of sequential entry. If only one firm is in the market it behaves like a monopolist but as soon as the second firm follows, they compete in a standard duopoly. Even though the model extends over two periods, discounting is not taken into consideration for reason of concise exposition. Although, depending on the size of the discount rate, it could play a decisive role.
Before starting the basic game that consists of two-firms and two-periods,

[14]For similar approaches see Tesoriere (2008) or Femminis and Martini (2010).

[15]Imitation costs are not considered and the spillovers are exogenous. For more information see Jin and Troege (2006). Though they use endogenous spillovers they give a good overview of the regarding literature.

the monopoly case is sketched in the following subsection, since the strategic effect becomes visible by setting its monopolistic investment decision in contrast to the behavior if a rival comes into play. Besides the monopoly results are needed for the later Stackelberg-Spence-Dixit interpretation.

3.2 Monopoly

The pure monopoly case occurs if only one firm enters the market knowing that no other firm does. The profit of the monopolist is given by

$$\pi^M = \Pi_1^M + \Pi_2^M - R^M - f, \tag{1}$$

where π^M is the overall profit, Π_t^M are the short-run profits in period 1 and 2, R^M are the R&D expenditures, and f is the fixed entry cost. Inserting the above stated functions gives

$$\pi^M = (a - q_1)q_1 - (c - x_M)q_1 + (a - q_2)q_2 - (c - x_M)q_2 - \frac{\gamma x_M^2}{2} - f. \tag{2}$$

From now on $a - c \equiv d$, whereas d is assumed to be positive. In the first stage, the firm chooses its R&D investment and in the second it sells the product in period one and two, following the general monopolistic profit maximization behavior. Solving by backward induction, the first derivatives with respect to q_1 and q_2 give the optimal output in terms of x_M: $q_t^M(x_M) = \frac{d+x_M}{2}$. Plugging those back into the profit function and optimizing it with respect to x_M yields the optimal cost reduction by R&D:

$$x_M = \frac{d}{\gamma - 1} \tag{3}$$

Thus the monopolist is investing in R&D as long as $\gamma > 1$[16]. Its investment decision is determined by the optimization condition that marginal benefit of investing in R&D has to equal the marginal costs of the investment, where $2\left(\frac{d+x_M}{2}\right)$ is the marginal benefit and γx_M the marginal cost.

[16] Note that Rossell and Walker (1999) use for their simulation to show the case of solicited entry $\gamma = 0.65$ for the same R&D cost function.

Next, the optimal supply for both periods can be calculated by inserting (3) into $q_t^M(x_M)$

$$q_t^M = \frac{d\gamma}{2\gamma - 1}. \tag{4}$$

The resulting profit and welfare, whereas the latter is defined as the sum of consumer surplus[17] and profit, are then given by:

$$\pi^M = \frac{d^2\gamma}{2(\gamma - 1)} - f \tag{5}$$

$$W^M = \frac{d^2\gamma(3\gamma - 2)}{4(\gamma - 1)^2} - f \tag{6}$$

In the whole analytical part the welfare is stated for the sake of completeness, although a detailed welfare analysis is out of the scope of the paper. Anyway, section 4.4 gives a short grading to see if there is need for political action.

3.3 Duopoly

So far there is only one active firm in the market, but the basic model that is introduced in this section consists of two competing firms. The firms decide in a precompetitive stage if they want to enter early or late and then optimize their profit via R&D outputs and quantities. Firstly, this prestage is presented. Secondly, the two cases of simultaneously entry and the sequential game are shown formally. The Stackelberg-Spence-Dixit interpretation in the last subsection represents the core of the model.

3.3.1 Precompetitive stage

The timing in the model is endogenous. This means that the two firms can decide to enter in the first or second period or even to stay out of the market. Since the firms are homogeneous but still a Stackelberg equilibrium can be played, a foundation to assign the entrance order is needed. Tesoriere (2008) uses for a very similar problem the approach of Hamilton and Slutsky (1990): They added a so-called "precompetitive stage" to the basic duopolistic game

[17]Which is in this case is the squared quantity: $CS^M = \left(\frac{d\gamma}{2\gamma-1}\right)^2$

in which the Stackelberg leadership is determined. In this precompetitive stage, the two firms simultaneously and independently commit to enter in the first or second period. The decision tree (figure 1) shows graphically the decisions in the precompetitive stage with all possible actions and subsequent games.

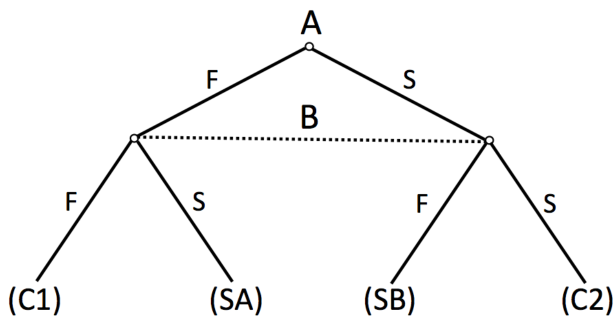

Figure 1: Decision tree based on Hamilton and Slutsky (1990)

If both firms move early, a symmetric Cournot starting in period one is played (C1). Similarly, if both firms decide to move late, (C2) will be played, which stands for a Cournot game that starts in the second period. (SA) and (SB) are the Stackelberg duopoly games, where in (SA) firm A is the Stackelberg leader since it enters in the first period and firm B is the follower. Consequently, (SB) results if firm B is the first-mover and A follows in the second period. As soon as the entrance announcements are made, they become common knowledge, such that the basic setting of the model is a static game of complete information, where firm A and B are players, the strategy space consists of entry in the first or second period and the corresponding profits are the payoff functions. It is highly relevant that the firms know their rivals' action before they invest in R&D since this decision differs from one with uncertainty. In a new market like the one for renewable energy, where political attention is high and basic research of great importance, one can imagine that firms are well informed about upcoming projects of competitors. This might particularly be the case when construction time needs to be taken into consideration. Another reason for the approach is that it allows additional information about the market structure that will arise. This is why we follow Tesoriere by applying the approach of Hamilton and Slutsky, such that the firms can expect a simultaneous or a sequential game before they invest in R&D and come into the market.

3.3.2 Simultaneous R&D investment and market entry

Firm A and B are ex-ante identical. Therefore it may seem obvious that both firms enter the market at the same time, either in the first or in the second period. In this subsection, these two simultaneous cases are considered.

Entry in period one (C1)

Both firms decide to pioneer new technologies and enter the market in the first period. In the second period the attained R&D output spills over to the rival. The profit of firm i thus consists of the short-run profits in period one and two, subtracted by the R&D expenditures and the fixed entry costs f. Because of the disclosure lag, R&D spillovers only occur in period two.

$$\pi_A^{C1} = (d + x_A - q_{A,1} - q_{B,1})q_{A,1} + (d + x_A + \beta x_B - q_{A,2} - q_{B,2})q_{A,2} - \frac{\gamma x_A^2}{2} - f \quad (7)$$

$$\pi_B^{C1} = (d + x_B - q_{A,1} - q_{B,1})q_{B,1} + (d + x_B + \beta x_A - q_{A,2} - q_{B,2})q_{B,2} - \frac{\gamma x_B^2}{2} - f \quad (8)$$

The profit optimization problem is solved by backwards induction. To do so, first the optimal behavior on the product market is determined, taking the investment decision as given. Therefore, the derivatives of the profit functions with respect to the quantities are taken, which leads to the best response functions:

$$BR_{A,1}(q_{B,1}, x_A) = \frac{d + x_A - q_{B,1}}{2} \quad (9)$$

$$BR_{B,1}(q_{A,1}, x_B) = \frac{d + x_B - q_{A,1}}{2} \quad (10)$$

$$BR_{A,2}(q_{B,2}, x_A, x_B) = \frac{d + x_A + \beta x_B - q_{B,2}}{2} \quad (11)$$

$$BR_{B,2}(q_{A,2}, x_A, x_B) = \frac{d + x_B + \beta x_A - q_{A,2}}{2} \quad (12)$$

Plugging the best response functions into each other leads to the supplied quantities $q_{i,t}$ of firm A and B in period one and two in terms of x_A and x_B:

$$q^{C1}_{A,1}(x_A, x_B) = \frac{d + 2x_A - x_B}{3} \tag{13}$$

$$q^{C1}_{B,1}(x_A, x_B) = \frac{d + 2x_B - x_A}{3} \tag{14}$$

$$q^{C1}_{A,2}(x_A, x_B) = \frac{d + (2-\beta)x_A + (2\beta - 1)x_B}{3} \tag{15}$$

$$q^{C1}_{B,2}(x_A, x_B) = \frac{d + (2-\beta)x_B + (2\beta - 1)x_A}{3} \tag{16}$$

Consider the difference between $q^{C1}_{i,1}$ and $q^{C1}_{i,2}$ that originates from the delayed spillover effect. For no spillovers ($\beta = 0$) both would be symmetric.
Inserting all $q^{C1}_{i,t}(x_A, x_B)$ back in π^{C1}_i and taking the F.O.C.s with respect to x_i gives the best response functions for the optimal R&D investment of one firm based on the other firms' R&D investment:

$$BR_{x_A}(x_B) = \frac{2((\beta - 4)d + (2\beta^2 - 5\beta + 4)x_B)}{16 - 8\beta + 2\beta^2 - 9\gamma} \tag{17}$$

$$BR_{x_B}(x_A) = \frac{2((\beta - 4)d + (2\beta^2 - 5\beta + 4)x_A)}{16 - 8\beta + 2\beta^2 - 9\gamma} \tag{18}$$

From those equations we can determine the equilibrium investment, respectively R&D output, by plugging them into each other. The result is the same since both firms are identical.

$$x^{C1}_i = \frac{2d(4 - \beta)}{2\beta(\beta - 1) - 8 + 9\gamma} \tag{19}$$

From those unit cost savings due to R&D we get the outputs

$$q^{C1}_{i,1} = \frac{d(9\gamma + 2\beta(\beta - 2))}{3(2\beta(\beta - 1) - 8 + 9\gamma)} \text{ and } q^{C1}_{i,2} = \frac{d(9\gamma + 4\beta)}{3(2\beta(\beta - 1) - 8 + 9\gamma)}. \tag{20}$$

Afterwards profits, consumer surplus, and welfare can be calculated:

$$\pi_i^{C1} = \frac{2d^2(2\beta^2(8+(\beta-4)\beta)+9(\beta(8+\beta)-16)\gamma+81\gamma^2)}{9(2\beta(\beta-1)-8+9\gamma)^2} - f \tag{21}$$

$$CS^{C1} = \frac{4d^2(2\beta^2(8+(\beta-4)\beta)+18\beta^2\gamma+81\gamma^2)}{9(2\beta(\beta-1)-8+9\gamma)^2} \tag{22}$$

$$W^{C1} = \frac{4d^2(4\beta^2(8+(\beta-4)\beta)+9(4+\beta)(3\beta-4)\gamma+162\gamma^2)}{9(2\beta(\beta-1)-8+9\gamma)^2} - 2f. \tag{23}$$

(For $\pi_i^{C1} < 0$ no entry occurs such that the profit is zero, which also changes consumer surplus and welfare.)

Entry in period two (C2)

This paragraph is structured like the preceding, only the starting point differs. Now both firms wait until the second period with their R&D investment and afterwards compete on the market. Thus the profit functions read

$$\pi_A^{C2} = (d+x_A-q_{A,2}-q_{B,2})q_{A,2} - \frac{\gamma x_A^2}{2} - f \tag{24}$$

$$\pi_B^{C2} = (d+x_B-q_{A,2}-q_{B,2})q_{B,2} - \frac{\gamma x_B^2}{2} - f. \tag{25}$$

Again, spillovers arise with a delay of one period and thus do not appear in the profit functions. Because of that, the best response functions for the quantities are only in terms of the own x. But since the R&D output mirrors in lower marginal costs and the firms enter the rival's costs in their output decision, one can find both R&D outputs in the equations for the optimal quantities.

$$BR_{A,2}(q_{B,2}, x_A) = \frac{d+x_A-q_{B,2}}{2} \tag{26}$$

$$BR_{B,2}(q_{A,2}, x_B) = \frac{d+x_B-q_{A,2}}{2} \tag{27}$$

$$q_{A,2}^{C2}(x_A) = \frac{d + 2x_A - x_B}{3} \tag{28}$$

$$q_{B,2}^{C2}(x_B) = \frac{d + 2x_B - x_A}{3} \tag{29}$$

Plugging the quantities back in the profit functions (24) and (25), and taking the derivatives with respect to the R&D outcomes yields the optimal investment.

$$x_A(x_B) = \frac{4(d - x_B)}{9\gamma - 8}, \quad x_B(x_A) = \frac{4(d - x_A)}{9\gamma - 8} \tag{30}$$

$$\Rightarrow x_i^{C2} = \frac{4d}{9\gamma - 4} \tag{31}$$

That implies for the quantities $q_{i,2}^{C2} = \frac{3d\gamma}{9\gamma - 4}$, which then results in the following firm profit, consumer surplus, and welfare:

$$\pi_i^{C2} = \frac{d^2\gamma(9\gamma - 8)}{(9\gamma - 4)^2} - f \tag{32}$$

$$CS^{C2} = \frac{18d^2\gamma^2}{(9\gamma - 4)^2} \tag{33}$$

$$W^{C2} = \frac{4d^2\gamma}{(9\gamma - 4)} - 2f \tag{34}$$

(Again, or $\pi_i^{C2} < 0$ no entry occurs such that the profit is zero, which also affects consumer surplus and welfare.)

3.3.3 Sequential R&D investment and market entry

This subsection is the main part of the model since it deals with the sequential move games on which the Stackelberg-Spence-Dixit terminology is applied later. One firm, for example firm A, enters the market in period one. The second firm B follows in period two. Since A becomes the Stackelberg leader, all results will be indexed with (SA). The first-comer A benefits from a lead-time in which it has temporary monopoly power. Its profit function consists of Π_1^A and Π_2^A since it operates for both periods. Nevertheless, the R&D expenditures R^A incurred only once, as well as the fixed market entry cost f. Since the rival is not in the market in period one, no spillovers occur for firm A. On the contrary, firm B takes advantage of A's R&D outcome but on the other hand misses the short-run profits from market period one.

$$\pi_A^{SA} = (d + x_A - q_{A,1})q_{A,1} + (d + x_A - q_{A,2} - q_{B,2})q_{A,2} - \frac{\gamma x_A^2}{2} - f \tag{35}$$

$$\pi_B^{SA} = (d + x_B + \beta x_A - q_{A,2} - q_{B,2})q_{B,2} - \frac{\gamma x_B^2}{2} - f \tag{36}$$

By the time when B makes its R&D decision, firm A's is already made and can be observed by B. Thus, firm A acts like a Stackelberg leader in R&D investments and B as the follower. Nevertheless, there is still a simultaneous Cournot competition in the product market. By again applying backwards induction the optimal output quantities are determined first.

Taking the first order condition with respect to $q_{A,1}$ gives the optimal output for incumbent A in period one as a function of x_A, which is the monopoly quantity that describes the major part of the first-mover-advantage:

$$q_{A,1}^{SA}(x_A) = \frac{d + x_A}{2} \tag{37}$$

Derivations of π_i^{SA} with respect to $q_{A,2}$ and $q_{B,2}$ lead to the best response functions for period two (equations (38) and (39)), which then subsequently result in functions in terms of R&D outcome x_A and x_B (equations (40) and (41)).

$$BR_{A,2}(q_{B,2}, x_A) = \frac{d + x_A - q_{B,2}}{2} \tag{38}$$

$$BR_{B,2}(q_{A,2}, x_A, x_B) = \frac{d + x_B + \beta x_A - q_{A,2}}{2} \tag{39}$$

$$q_{A,2}^{SA}(x_A, x_B) = \frac{d + (2 - \beta)x_A - x_B}{3} \tag{40}$$

$$q_{B,2}^{SA}(x_A, x_B) = \frac{d + 2x_B + (2\beta - 1)x_A}{3.} \tag{41}$$

For zero spillovers ($\beta = 0$), $q_{B,2}^{SA}$ and $q_{A,2}^{SA}$ are equal and the benefit of waiting does not exist.[18]

The profit functions depending on x_A and x_B read as follows:

$$\pi_A^{SA}(x_A, x_B) = \left(\frac{d + x_A}{2}\right)^2 + \left(\frac{d + (2-\beta)x_A - x_B}{3}\right)^2 - \frac{\gamma x_A^2}{2} - f \tag{42}$$

$$\pi_B^{SA}(x_A, x_B) = \left(\frac{d + 2x_B + (2\beta - 1)x_A}{3}\right)^2 - \frac{\gamma x_B^2}{2} - f \tag{43}$$

Firm A takes B's reaction on its R&D amount into consideration when making its investment decision. Therefore, B's optimal investment in terms of x_A is calculated first by optimizing its profit with respect to x_B:

$$x_B(x_A) = \frac{4(d + (2\beta - 1)x_A)}{9\gamma - 8} \tag{44}$$

Plugging this result into firm A's profit function and proceeding alike gives the optimal R&D output for firm A, which by plugging (45) into (44) leads to B's R&D investment.

$$x_A^{SA} = \frac{d(3\gamma(96 - 51\gamma + 4\beta(3\gamma - 4)) - 128)}{128 + \gamma(96\beta + 9\gamma(57 + 4\beta(\beta - 4)) - 162\gamma^2 - 464)} \tag{45}$$

$$x_B^{SA} = \frac{8d(16(\beta - 1) + \gamma(29 + 3\beta(2\beta - 9)) - 9\gamma^2)}{128 + \gamma(96\beta + 9\gamma(57 + 4\beta(\beta - 4)) - 162\gamma^2 - 464)} \tag{46}$$

With x_A^{SA} and x_B^{SA} the equilibrium outputs can be calculated:

$$q_{A,1}^{SA} = \frac{1}{2}(d + \frac{d(3\gamma(96 - 51\gamma + 4\beta(3\gamma - 4)) - 128)}{128 + \gamma(96\beta + 9\gamma(57 + 4\beta(\beta - 4)) - 162\gamma^2 - 464)} \tag{47}$$

$$q_{A,2}^{SA} = \frac{d\gamma(5 + 3\beta - 6\gamma)(9\gamma - 8)}{128 + \gamma(96\beta + 9\gamma(57 + 4\beta(\beta - 4)) - 162\gamma^2 - 464)} \tag{48}$$

$$q_{B,2}^{SA} = \frac{6d\gamma(16(1-\beta) - 29\gamma + 3\beta\gamma(9 - 2\beta) + 9\gamma^2}{\gamma(464 - 96\beta) - 9\gamma^2(57 + 4\beta(\beta - 4)) + 162\gamma^3 - 128}. \tag{49}$$

[18] An interpretation for large spillover can be found in the numerical example in the next chapter.

Profits (if not negative and therefore zero), consumer surplus, and welfare in the sequential game are

$$\pi_A^{SA} = \frac{d^2\gamma(128 + 3\gamma(39\gamma - 86 - 6\beta(\beta - 2))}{32\gamma(29 - 6\beta) - 18\gamma^2(57 + 4\beta(\beta - 4)) + 324\gamma^3 - 256} - f \tag{50}$$

$$\pi_B^{SA} = \frac{4d^2\gamma(9\gamma - 8)(16(1 - \beta) - 29\gamma + 3\beta\gamma(9 - 2\beta) + 9\gamma^2)^2}{\gamma(464 - 96\beta) - 9\gamma^2(57 + 4\beta(\beta - 4)) + 162\gamma^3)^2 - 128} - f \tag{51}$$

$$CS^{SA} = \frac{1}{2}\left(\frac{1}{2}\left(d + \frac{d(3\gamma(96 - 51\gamma + 4\beta(3\gamma - 4))128)}{128 + \gamma(96\beta + 9\gamma(57 + 4\beta(\beta - 4) - 162\gamma^2 - 464)}\right)\right)^2$$
$$+ \frac{1}{2}\left(\frac{d\gamma(136 - 36\beta^2\gamma + 9\beta(15\gamma - 8) + 3\gamma(36\gamma - 89))}{\gamma(464 - 96\beta) - 128 - 9\gamma^2(57 + 4\beta(\beta - 4)) + 162\gamma^3}\right)^2 \tag{52}$$

$$W^{SA} = \pi_A^{SA} + \pi_B^{SA} + CS^{SA}. \tag{53}$$

3.4 Stackelberg-Spence-Dixit interpretation

If the sequential game occurs after the precompetitive stage, the prime mover has more strategic options than the in (SA) already implemented Stackelberg leadership in R&D investment and the standard Cournot Nash behavior on the product market. According to Tirole (1994), an incumbent firm can try to build up a barrier to entry such that the potential entrant stays out of the market. In Tirole's Stackelberg-Spence-Dixit model, the incumbent firm builds up capacity which then can be seen as sunk costs and thus builds a credible threat that it will supply a higher amount of the good than under Stackelberg or Cournot competition.[19]

Applied on this model, the incumbent firm can strategically change its R&D investment to deter the follower's entry and in this way stays monopolist in the second period too. To make use of it, it is necessary to take a closer look

[19]See the literature review for a detailed explanation of the model.

on the effect that firm A's R&D investment has on B's profit:

$$\pi_B^{SA}(x_A) = \left(\frac{d + 2x_B(x_A) + (2\beta - 1)x_A}{3}\right)^2 - \frac{\gamma(x_B(x_A))^2}{2} - f$$

$$= \frac{(d + (2\beta - 1)x_A)^2\gamma}{9\gamma - 8} - f \tag{54}$$

Taking the derivative of $\pi_B^{sa}(x_A)$ with respect to x_A yields

$$\frac{\partial \pi_B^{SA}(x_A)}{\partial x_A} = \frac{2\gamma(2\beta - 1)(d + (2\beta - 1)x_A)}{9\gamma - 8}. \tag{55}$$

(55) can be positive or negative, since $d > 0, \gamma > 1$, $0 \leq \beta \leq 1$, and $x_A \geq 0$. For $\beta > \frac{1}{2}$, the effect is always positive. This implies that if firm A is investing in R&D, the profit of firm B rises due to the spillover, since it reduces B's marginal cost and therewith increases its competitiveness and profitability without incurring investment costs. Hence, if incumbent A wants to deter B's entry by use of strategic R&D investment, he has to under-invest compared to the case (SA) considered earlier.[20] For small R&D spillover rates ($\beta < \frac{1}{2}$) and $d > |(2\beta - 1)x_A|$ the opposite case occurs. Now the negative effect of a higher competitiveness of firm A due to lower unit costs generated by more investment outweighs the positive spillover effect - the classical entrance deterrence by over-investment can be obtained.[21] Nevertheless, the focus of the present model is on the possibility of entrance deterrence by under-investment, which can only be applicable if $\beta > \frac{1}{2}$.[22] Hence, the following section examines if the three implications of the Stackelberg-Spence-Dixit approach can be observed in this manner.

[20]The same holds for $\beta < \frac{1}{2}$ and $d < |(2\beta - 1)x_A|$, which can be neglected for our purpose.

[21]For instance, De Bondt and Veugelers (1991) investigate that for zero spillovers, over-investment occurs.

[22]Jensen (1992) finds that there will be no under-investment in equilibrium for relatively small spillovers.

The below options will be considered:

1. Entry is called blockaded if $\pi_B^{SA}(x_A^M) \leq 0$ where $x_A^M = x_M = x_A^{blo}$.
2. Entry deterrence takes place if
$x_A^{det} : \pi_B^{SA}(x_A^{det}) \leq 0$ for $x_A^{det} < x_A^{SA}$ or
$x_A^{det} : \pi_B^{SA}(x_A^{det}) \leq 0$ for $x_A^{det} > x_A^{SA}$ but $x_A^{det} < x^M$
3. Entry is accommodated if $\pi_A(x_A^{det}) \leq \pi_A(x_A^{acc})$ with $x_A^{acc} = x_A^{SA}$, $x_A^{acc} > x_A^{det}$.

3.4.1 Blockaded entry

Entry is blockaded if

$$\pi_B^{SA}(x_M) = \frac{(d + (2\beta - 1)x_M)^2 \gamma}{9\gamma - 8} - f \leq 0, \tag{56}$$

so if the potential entrant B cannot cover its fixed costs after firm A has invested like a monopolist und thus stays out of the market. The decisive variable in this case is this fixed entrance cost f. How large does it need to be such that firm A can hinder B from entering the market by setting R&D at its monopoly optimum?
From (3) we get $x_M = \frac{d}{\gamma - 1}$. Plugging this into B's profit function (56) and solving the equation for f yields

$$f^{blo} \geq \frac{d^2 \gamma (2\beta - 2 + \gamma)^2}{(\gamma - 1)^2 (9\gamma - 8)}. \tag{57}$$

Accordingly, if f is higher than this critical value, firm A can blockade B's market entry by acting like a monopolist. Since the two firms are homogenous, A faces the same market entry costs as B, and therewith this possibility is only provided for $f^{blo} \leq \Pi_1^M + \Pi_2^M - R^M$ (see (1)). Verbally, as in general, firm A only enters if it can make a positive or at least zero profit.

3.4.2 Entrance deterrence

Firm B will only enter the market in period two if a positive profit can be gained[23]: $\pi_B^{SA}(x_A) > 0$. Thus, if the profit by setting $x_A = x_M$ is positive, a incumbent with entry deterrence motive has to set its R&D effort such that $\pi_B^{SA}(x_A^{det}) \leq 0$, which needs to be lower than x_M in the considered case of under-investment, since the effect of A's R&D on B's profit is positive for the assumed large spillover parameter. With B's profit function in terms of x_A (54), the condition for entry deterrence reads

$$\pi_B^{SA}(x_A^{det}) = \frac{(d + (2\beta - 1)x_A^{det})^2\gamma}{9\gamma - 8} - f = 0. \tag{58}$$

The solution of this quadratic equation yields two possible values for x_A^{det}:

$$x_{A,1}^{det} = \frac{-d}{(2\beta - 1)} - \frac{\sqrt{f\gamma(9\gamma - 8)}}{(2\beta - 1)\gamma} \tag{59}$$

$$x_{A,2}^{det} = \frac{-d}{(2\beta - 1)} + \frac{\sqrt{f\gamma(9\gamma - 8)}}{(2\beta - 1)\gamma} \tag{60}$$

(with $\beta \neq \frac{1}{2}$)

Since firm A is interested in the smallest deviation from its optimum R&D and the effect of x_A on B's profit is positive for $\beta > \frac{1}{2}$, it chooses the larger value that just deters firm B's entry. Due to the strict positive square root and denominator, $x_{A,1}^{det} \leq x_{A,2}^{det}$ and thus from now on only $x_{A,2}^{det}$ is considered. In the following, $x_{A,2}^{det} \equiv x_A^{det}$. Again, the result depends primary on the fixed entrance fee f: The smaller f, the smaller x_A^{det} needs to be, whereby two cases can be distinguished:

Firstly, if f lies in the moderate interval determined shortly, firm A can deter B's entry by investing less than it would do in the standard (SA) game, which is called "entry deterrence (SA)". This means that the higher the anyway existing entrance hurdle f, the less firm A has to under-invest compared to their Stackelberg equilibrium investment x_A^{SA} to deter B's entry. To get an

[23] In case of zero profit firm B is indifferent between entering or staying out.

economically meaningful result, x_A^{det} needs to be positive such that for $\beta > \frac{1}{2}$:

$$\left|\frac{d}{(2\beta-1)}\right| < \frac{\sqrt{f\gamma(9\gamma-8)}}{(2\beta-1)\gamma} \tag{61}$$

Solving (61) for f yields the lower range of valid results (f_l^{det}):

$$f_l^{det} > \frac{d^2\gamma}{9\gamma-8} \tag{62}$$

The fixed entrance fee f needs to be bigger than $\frac{d^2\gamma}{9\gamma-8}$ such that firm A can deter B's entry. Note that it does not depend on the spillover parameter β. The interpretation is trivial: Firm B's profit if A is not investing is given by $\pi_B^{SA}(x_A^{SA}=0) = \frac{d^2\gamma}{9\gamma-8} - f$. The possibility of entry deterrence by under-investment only exists if the entrance costs f are higher than the benefit firm B can make on basis of its own investment, since the lowest feasible investment firm A can make is none. If A is not investing, there will be no knowledge generation and as a consequence no spillovers. So for all $f < f_l^{det}$ firm A has no options to deter B's entry.

The upper boundary for f is determined by $x_A^{det} < x_A^{SA}$ (since we are here interested in under-investment compared to x_A^{SA}), such that it can be further circumscribed by

$$\frac{-d}{(2\beta-1)} + \frac{\sqrt{f\gamma(9\gamma-8)}}{(2\beta-1)\gamma} < \frac{d(3\gamma(96-51\gamma+4\beta(3\gamma-4))-128)}{128+\gamma(96\beta+9\gamma(57+4\beta(\beta-4))-162\gamma^2-464)} \tag{63}$$

$$\Rightarrow f_u^{det} < \frac{4d^2\gamma(9\gamma-8)(16(1-\beta)-29\gamma+3\beta\gamma(9-2\beta)+9\gamma^2)^2}{(\gamma(464-96\beta)-9\gamma^2(57+4\beta(\beta-4))+162\gamma^3)^2-128}. \tag{64}$$

A comparison with (51) shows that this upper bound is exactly B's profit before subtracting the fixed cost f. This is because it shows the fixed cost that is necessary to equalize x_A^{SA} and x_A^{det}. Since x_A^{det} always yields in zero profits for firm B, the upper bound f_u^{det} must be equal to the benefit without the fixed cost for x_A^{SA}. Putting both together gives the first range of f for that entry deterrence by under-investment is an option:

$$\frac{d^2\gamma}{9\gamma-8} < f < \frac{4d^2\gamma(9\gamma-8)(16(1-\beta)-29\gamma+3\beta\gamma(9-2\beta)+9\gamma^2)^2}{(\gamma(464-96\beta)-9\gamma^2(57+4\beta(\beta-4))+162\gamma^3)^2-128} \quad (65)$$

The second case begins at the just now identified upper boundary. For all f bigger than f_u^{det} it holds that $x_A^{det} > x_A^{SA}$ instead of lower, which would surprisingly be a over-investment although the derivation (55) is positive for large values of β. As already described, once f is just equal to this critical value, firm B would make zero profits if firm A acts like a Stackelberg leader in R&D investments. Thus, for each increase of f firm B would make a loss and hence would not enter if A plays x_A^{SA}. In other words, the fixed entry costs are sufficiently high to prevent the entry. Due to that, firm A has space to bring its investments closer to its first best optimum, which is the monopoly amount x^M. Thereby it increases its R&D just as much as it still does not exceed x_A^{det} to keep firm B out of the market. Putting it like this makes clear that it is not a case of strategic over-investment to deter a potential follower's entry but just the opposite, as the upper boundary of the second interval for f (entry deterrence (M)) shows:

In this interval, firm A knows that in case of a Stackelberg game in investments and a Cournot duopoly in the product market the fixed cost is high enough to form a natural barrier to entry. Thus it would like to switch to monopoly investments. But as calculated for the case of blockaded entry, f must be at least as high as f^{blo} to keep the monopoly position. As long as the level of fixed cost is lower than f^{blo}, firm A has to under-invest compared to its monopoly investment to keep firm B from entering the market, because x^M would create too many spillovers such that market entry is getting profitable despite f. As a result, in the range

$$\frac{4d^2\gamma(9\gamma-8)(16(1-\beta)-29\gamma+3\beta\gamma(9-2\beta)+9\gamma^2)^2}{(\gamma(464-96\beta)-9\gamma^2(57+4\beta(\beta-4))+162\gamma^3)^2-128} < f < \frac{d^2\gamma(2\beta-2+\gamma)^2}{(\gamma-1)^2(9\gamma-8)} \quad (66)$$

firm B's entry in case of simultaneous entry is always prevented but firm A cannot switch to x^M without enabling B to make positive profits. Thus, firm A can deter B's potential entry by investing x_A^{det}.
Graphic (2) shows the different sections of f.

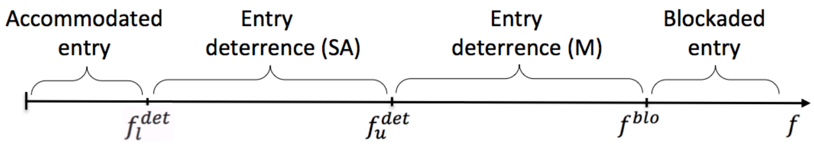

Figure 2: Strategic options conditional on the fixed market entry cost

For f greater than f_l^{det} the first-mover can deter the followers entry by under-investment compared to x_A^{SA} (entry deterrence (SA)). As soon as the fixed costs are higher or equal to f_u^{det} they build a natural barrier to entry for the second mover, why the first-mover wants to switch to the monopoly investment x^M. Due to the spillovers, A's high investments generate a positive profit for B such that it still wants to enter. Therefore, firm A under-invests in R&D compared to x^M to keep firm B out of the market (entry deterrence (M)). As soon as f^{blo} is reached the first-mover can behave as a monopolist. This arrow is also of interest for the last option of the first-mover presented now: Accommodated entry.

3.4.3 Accommodated entry

If the incumbent firm A does not deter entry, whether it cannot or does not want to, it is called to play accommodated entry. Latter will be the case if $\pi_A(x_A^{det}) \leq \pi_A(x_A^{acc})$ with $x_A^{acc} = x_A^{SA}$. Furthermore, as we are interested in entrance deterrence through under-investment, $x_A^{det} < x_A^{acc}$ still needs to be fulfilled. Intuitively, the higher the necessary deviation from the optimal Stackelberg leadership investment to the lower deterrence amount, the more attractive does it become to accept the entrant. From analyzing entrance deterrence we know that for all $f < f_l^{det}$ firm A is not able to keep firm B out of the market and thus is compelled to play accommodated entry.

In general, firm A would choose accommodated entry if it yields a higher profit than entrance deterrence. Since x_A^{det} guarantees firm A full monopoly power, its profit reads

$$\begin{aligned}\pi_M(x_A^{det}) &= 2\left(\frac{d+x_A^{det}}{2}\right)^2 - \frac{\gamma(x_A^{det})^2}{2} - f \\ &= 2\left(\frac{d+\left(\frac{-d}{(2\beta-1)}+\frac{\sqrt{f\gamma(9\gamma-8)}}{(2\beta-1)\gamma}\right)}{2}\right)^2 - \frac{\gamma\left(\frac{-d}{(2\beta-1)}+\frac{\sqrt{f\gamma(9\gamma-8)}}{(2\beta-1)\gamma}\right)^2}{2} - f \\ &= \frac{f(\gamma(15-8\beta(\beta-1)-9\gamma)-8)}{2\gamma(2\beta-1)^2} \\ &\quad + \frac{d(d\gamma(4(\beta-1)^2-\gamma)+2(2(\beta-1)+\gamma)\sqrt{f\gamma(9\gamma-8)})}{2\gamma(2\beta-1)^2}\end{aligned} \tag{67}$$

It is important to notice that once firm A made its investment decision, it is fixed and cannot be changed anymore. This is important since the first-mover advantage here exists if the incumbent can credibly commit to a choice that he would like to correct as soon as the other firm decides to stay out of the market. In this case, firm A would later like to invest x_M but its investment decision is unchangeable. Therefore, firm A's profit is less than the uncontested monopoly profit.

The comparison stated in the beginning additionally requires $\pi_A(x_A^{acc})$, which is simply (50) since $x_A^{acc} = x_A^{SA}$. Firm A chooses accommodated entry if

$$\pi_A(x_A^{det}(f)) \leq \pi_A(x_A^{acc}(f)) \tag{68}$$

$$\frac{f(\gamma(15-8\beta(\beta-1)-9\gamma)-8)}{2\gamma(2\beta-1)^2+}$$

$$+\frac{d(d\gamma(4(\beta-1)^2-\gamma)+2(2(\beta-1)+\gamma)\sqrt{f\gamma(9\gamma-8)})}{2\gamma(2\beta-1)^2} \tag{69}$$

$$\leq \frac{d^2\gamma(128+3\gamma(39\gamma-86-6\beta(\beta-2))}{32\gamma(29-6\beta)-18\gamma^2(57+4\beta(\beta-4))+324\gamma^3-256}-f$$

Solving this inequation gives the critical values for f. For reasons of complexity the result is not calculated here but in the numerical example in the next chapter. Theoretically, for all f higher than the critical one, the incumbent firm wants to deter the follower's entry. If f is lower, it is too costly to play entrance deterrence and thus it accepts the entry of the second firm. It is important to notice that the firms only operate if positive profits can be gained. Further, negative R&D outputs are not an option. Both could lead to a rejection of the critical value of f. This would imply that if deterrence is possible, the first-mover always deters or never, independently of f. We have already seen in case of deterred entry that if f is smaller than the lower bound (62), firm A would need a negative R&D output to keep B out of the market. Since this is, as already said, not an option, firm A always plays accommodated entry.

4 Interpretation on basis of a numerical example

To get a better intuition for the model and its implications, the results are now shown in a simplified version, where partly values are assigned for the parameters. Firstly, β is set equal to 1, which implies perfect spillovers. It is obviously that if entry deterrence by under-investment is possible, it simplest can be pointed out if all of the learning spills over from the originator to the recipient and imitation of the knowledge happens without losses. The type of R&D regarding our example is classified as basic research[24], where the

[24] Popp (2006) found that patents in energy technology spawned by government R&D are cited more often than others, which is in line with the notion that this rather basic

spillover rates are assumed to be considerably large (e.g. Lilien and Yoon, 1990 and Edenhofer et al. 2013). Additionally, an empirical study by Braun et al. (2010) confirms that in the field of renewable energies (wind and solar), innovations are strongly driven by knowledge spillovers, which is in line with a large spillover parameter. On the other hand, Bjorner and Mackenhauer (2013) reject that there are more spillovers within the renewable energy research compared to other types of private research. However, this is primarily an argument against R&D subsidies but does not necessarily disagree a high spillover rate. Since β does not play a role for the monopolist and in the case of simultaneous entry (C2), the results from above do not change due to this simplification and thus want be replicated in this chapter. Nevertheless, they will be used for comparison. Secondly, this simplification is partly supplemented by the assumptions $\gamma = 3$ and $d = 30$[25], if it is more convenient to act with example values. Those will primarily be found when it comes to the Spence-Dixit-Interpretation, the game-theoretical comparison (section 4.3) of the results and in tables in the appendix.

4.1 Basic game

Simultaneous market entry in period one (C1)

Starting point are the profit maximization functions (7) and (8), with $\beta = 1$. Following the same course of action as in the chapter above leads to the best response functions for optimal R&D output and the resultant values.

$$BR_{x_A}(x_B) = \frac{2(3d - x_B)}{9\gamma - 10} \tag{70}$$

$$BR_{x_B}(x_A) = \frac{2(3d - x_A)}{9\gamma - 10} \tag{71}$$

$$x_i^{C1} = \frac{6d}{9\gamma - 8} \tag{72}$$

research.

[25]De Bondt and Veugelers (1991), for instance, chose $\gamma = 30$ and $d = 100$. Applying those numbers instead of the actual would not change direction and interpretation of the results but its clarity.

For each value of γ and d the industry investments are higher than in a monopoly market, but the per firm R&D investment is lower. Unsurprisingly, the perfect spillovers result in a negative investment connectedness. The more one firm is investing, the less is the intension for the other one and vice versa. Since the firms are homogenous, we get a symmetric Cournot Nash equilibrium in R&D investments, ensuing symmetric outputs in the market, which then result in equal profits.

$$q_{i,1}^{C1} = \frac{d(9\gamma - 2)}{3(9\gamma - 8)} \text{ and } q_{i,2}^{C1} = \frac{d(9\gamma + 4)}{3(9\gamma - 8)} \tag{73}$$

$$\pi_i^{C1} = \frac{2d^2(9\gamma - 5)(9\gamma - 2)}{9(8 - 9\gamma)^2} - f \tag{74}$$

The output quantities are larger in the second period then in the first. The reason for this is that the unit costs in period two are lower because of the R&D spillovers. The produced quantities are larger in the duopoly than under monopoly and per firm and industry profit is lower compared to a market with only one firm. Altogether this leads to a higher consumer surplus and a higher welfare than in the monopoly case (compare (76) with (6)).

$$CS^{C1} = \frac{4d^2(10 + 9\gamma(2 + 9\gamma))}{9(8 - 9\gamma)^2} \tag{75}$$

$$W^{C1} = \frac{4d^2(20 + 9\gamma(18\gamma - 5))}{9(8 - 9\gamma)^2} - 2f \tag{76}$$

The numerical results for the chosen values and different fixed cost f can be found in the appendix.

Simultaneous market entry in period two (C2)

As already mentioned, for the case that both firms enter the market in the second period, no spillovers occur. Thus, we can simply adopt the general results from earlier since the simplification $\beta = 1$ does not matter. It is obvious that compared to (C1) everything will be lower, since the firms operate for only one period instead of two. That negatively affects the consumer surplus and welfare. The numerical results for the second simplification are also shown in the appendix.

Sequential R&D investment and market entry (SA)

In the last case of the basic game only the profit function of the second moving firm changes by fixing β to 1, since the firms enter sequentially and thus only the latter can benefit from the positive spillover effect.

$$\pi_A^{SA} = (d + x_A - q_{A,1})q_{A,1} + (d + x_A - q_{A,2} - q_{B,2})q_{A,2} - \frac{\gamma x_A^2}{2} - f \quad (77)$$

$$\pi_B^{SA} = (d + x_B + x_A - q_{A,2} - q_{B,2})q_{B,2} - \frac{\gamma x_B^2}{2} - f \quad (78)$$

As a consequence, the first order condition of firm A with respect to output in period one remains unchanged (see (37)). The simplified versions of the best response functions for output in period two show that firm B treats A's investment as equal. In other words, for firm B the R&D outputs are perfect substitutes.

$$BR_{A,2}(q_{B,2}, x_A) = \frac{d + x_A - q_{B,2}}{2} \quad (79)$$

$$BR_{B,2}(q_{A,2}, x_A, x_B) = \frac{d + x_B + x_A - q_{A,2}}{2} \quad (80)$$

If it comes to the optimal quantities in terms of R&D investments, one can perfectly see the effect of $\beta = 1$, since the investments work in opposite directions:

$$q_{A,2}^{SA}(x_A, x_B) = \frac{d + x_A - x_B}{3} \quad (81)$$

$$q_{B,2}^{SA}(x_A, x_B) = \frac{d + 2x_B + x_A}{3} \quad (82)$$

Firm A as first-mover doesn't benefit from x_B but rather gets into a weaker position because as soon as B is not just entering the market but also investing, the once symmetric Cournot game ($x_B = 0$) changes into one with asymmetric costs and leads to an increase of firm B's production and a decrease of A's production output. Additionally, A's investments fully benefit B. That is the reason why firm A is not able to generate a cost advantage. Algebraically, in A's general function for its optimal output (40) the potential factor 2 in front of x_A vanishes compared to $\beta = 0$ and simultaneously x_A enters with a positive sign in B's output quantity (41). To see the overall effect of $\beta = 1$ on the investments, we proceed in the same way as in chapter 3.3.3. The profit functions depending on x_A and x_B read as follows:

$$\pi_A^{SA}(x_A, x_B) = \left(\frac{d + x_A}{2}\right)^2 + \left(\frac{d + x_A - x_B}{3}\right)^2 - \frac{\gamma x_A^2}{2} - f \tag{83}$$

$$\pi_B^{SA}(x_A, x_B) = \left(\frac{d + 2x_B + x_A}{3}\right)^2 - \frac{\gamma x_B^2}{2} - f \tag{84}$$

Applying backwards induction gives $x_B(x_A) = \frac{4(d+x_A)}{9\gamma-8}$ and therewith the optimal R&D investments:

$$x_A = \frac{d(3\gamma(96 - 51\gamma + 4(3\gamma - 4)) - 128)}{128 + \gamma(405\gamma - 162\gamma^2 - 368)} \tag{85}$$

$$x_B = \frac{8d\gamma(9\gamma - 8)}{\gamma(368 + 81\gamma(2\gamma - 5)) - 128} \tag{86}$$

It depends on γ whether firm A or B undertake higher investments. For all $\gamma > \frac{8}{45}(11+\sqrt{31})$, $x_A > x_B$ and for $1 < \gamma < \frac{8}{45}(11+\sqrt{31})$, firm B invests more ($x_A < x_B$). The explanation lies in the interacting marginal conditions. Both firms invest in R&D until the marginal benefit equals the marginal costs γx_i. One could expect that firm B does not invest at all but still profits by A's R&D outcome, however, since B can influence A's output quantity in period two by generating cost asymmetry, this would not be optimal. Furthermore, the marginal costs are increasing with the produced R&D outcome and are low (depending on γ) at the beginning. So for the early investment units the benefit outweighs its cost. A decrease in the value of γ thus leads to an increase in investments. Since firm A operates for two periods in the market, it has more opportunities to recoup its R&D expenditures, which reflects in higher marginal benefit and leads to more investments. In contrast, firm B enters only for the second period but on the other hand can profit from A's investments. If γ is higher than the critical value stated above, the effect of more operating time is crucial and $x_A > x_B$. In case of smaller γ, firm B can cheap build up a cost advantage over A that can be refinanced in only one period and therefore $x_A < x_B$. The total industry investment in (SA)[26] is always lower than in (C1) but the magnitude of the difference decreases in γ. The larger γ and therewith the costs, the more the R&D outputs converge. The R&D investments lead to the following quantities:

$$q_{A,1}^{SA} = \frac{d\gamma(8-9\gamma)^2}{\gamma(368+81\gamma(2\gamma-5))-128} \tag{87}$$

$$q_{A,2}^{SA} = \frac{2d\gamma(3\gamma-4)(9\gamma-8)}{\gamma(368+81\gamma(2\gamma-5))-128} \tag{88}$$

$$q_{B,2}^{SA} = \frac{6d\gamma^2(9\gamma-8)}{\gamma(368+81\gamma(2\gamma-5))-128} \tag{89}$$

Consider that the output of the incumbent in period one (87) is lower than under pure monopoly (4), although is the only player in the market. This is due to different R&D investments and therewith different cost reductions. The pure monopolist is not confronted with a potential entrant when optimizing its R&D decision, which leads to another cost reduction than if the first-moving firm takes the follower into account. Afterwards, when the firms optimize their output, the pure monopolist faces lower costs and thus sup-

[26] Given by $\frac{d(128+\gamma(189\gamma-304))}{\gamma(368+81\gamma(2\gamma-5))-128}$.

plies a higher quantity. This does not automatically imply that welfare is also higher in the pure monopoly case. Again the ranking depends on γ and f:

$$\pi_A^{SA} = \frac{d^2\gamma(128 + 3\gamma(39\gamma - 80))}{2\gamma(368 + 81\gamma(2\gamma - 5)) - 256} - f \tag{90}$$

$$\pi_B^{SA} = \frac{4d^2\gamma^3(9\gamma - 8)^3}{(\gamma(368 + 81\gamma(2\gamma - 5)) - 128)^2} - f \tag{91}$$

$$CS^{SA} = \frac{d^2\gamma^2(8 - 9\gamma)^2(128 + 3\gamma(75\gamma - 112))}{2(\gamma(368 + 81\gamma(2\gamma - 5)) - 128)^2} \tag{92}$$

$$W^{SA} = \frac{d^2\gamma(\gamma(86016+\gamma(27\gamma(9184+3\gamma(531\gamma-1993))-199168))-16384)}{2(\gamma(368+81\gamma(2\gamma-5))-128)^2} - 2f. \tag{93}$$

For high values of f welfare is larger if only one firm is in the market since the fixed costs add two times in (SA). Surprisingly, also without taking the fixed costs into consideration ($f = 0$) there exists a range, determined by γ, where $W^M > W^{SA}$. This is the case for small γ (since d cancels out, the value that equalizes the welfares is $\gamma_{crit} = 3.14569$). For larger values, W^{SA} is superior to W^M. The monopolist does not have to fear the second movers competition, so if R&D is getting too costly, she early decides to shorten the investments and sells a lower quantity. However, the first-mover in (SA) knows how the second-mover is going to act, and tries to weaken the asymmetric competition in period two, even if R&D is expensive.

Welfare in game (C1) is always superior to the welfare in (SA), because the same amount of fixed costs arise but both firms can benefit from spillovers and thus production costs are lower and quantities are higher. In addition, the markets in (C1) are more competitive since there is a Cournot duopoly in both periods instead of one duopoly and one monopoly as in (SA).
Like in the chapter above, the first-moving firm has the option to invest strategically and tries to deter the latecomer's entry. This case will be considered in the next section.

4.2 Stackelberg-Spence-Dixit interpretation

Like in the sections above, β is set equal to one. Firm A is again the first-mover and firm B would like to follow in period two. The analytical procedure is the same as in chapter 3.4, why it is not explicitly described here.
First of all the effect of x_A on firm B's profit is examined. The derivative of $\pi_B^{SA}(x_A)$ with respect to x_A yields

$$\frac{\partial \pi_B^{SA}(x_A)}{\partial x_A} = \frac{2\gamma(d + x_A)}{9\gamma - 8}, \tag{94}$$

which is strictly positive for all γ, d and x_A in the defined range. Thus, the basic assumption to examine entry deterrence by under-investment is fulfilled. This section is now structured as follows: Firstly, the critical fixed cost to blockade entry is calculated. Then the possibility of entrance deterrence is evaluated and interpreted based on our parameter assumptions, and in the third part these results will be compared to an accommodated entry.

4.2.1 Blockaded entry

Suggesting that only firm A is investing prior to period one, but firm two lies in wait, it would be optimal for A if the fixed costs were a sufficient hurdle to keep B out of the market, such that it can simply behave as a pure monopolist. The necessary fixed costs are given by

$$f^{blo} \geq \frac{d^2\gamma^3}{(\gamma - 1)^2(9\gamma - 8)}. \tag{95}$$

If f is at least as high as this equation requires, firm A can blockade B's entry with the monopoly R&D output x^M. Of course, this only works if f is sufficiently low in order to guarantee a positive profit for A.. Otherwise no firm will enter at all. For the example values $d = 30$ and $\gamma = 3$ it gets: $f^{blo} \geq 319.74$. A monopolist facing these parameters can make a profit of 675 before subtracting the fixed costs and thus blockades entry. This means that one firm will enter if the fixed costs are in a range of $319.74 < f < 675$. For smaller fixed cost the monopolist can still try to keep the other firm out of the market. This option will be checked in the next section.

4.2.2 Entrance deterrence

In a market with profit opportunities by pioneering new technologies, the first-moving firm faces the risk that competitors can use knowledge spillovers to overtake it. The first-mover is aware of that and has the intention to keep the others out of the market. One possible way would be a very high output quantity that lowers the price of the good in a way that the potential entrant is not able to cover its fixed costs. However, as soon as a second firm is in the market they compete in a standard Cournot duopoly and thus a high quantity is no credible threat as one can see in the output best response functions (79) and (80). In the Stackelberg-Spence-Dixit model this dilemma is solved by a preplay stage where the incumbent can build up capacity; the investment can then be seen as a sunk cost and thus the quantity argument becomes convincing. This is not possible here. By way of illustration one can think of electricity as the exemplary good in our model, which cannot be stored (unless at heavy cost). As a consequence, the influencing variable that could deter the follower's entry is the R&D output. As shown in the beginning of this chapter, there is a positive relation between the profit of the second moving firm B and the pioneers investment x_A, such that it has to under-invest compared to x_A^{SA} or x^M in order to keep B out of the market. The following equation shows the requirement for this R&D output for $\beta = 1$:

$$\pi_B^{SA}(x_A^{det}) = \frac{(d + x_A^{det})^2 \gamma}{9\gamma - 8} - f = 0 \qquad (96)$$

The interpretation is the same as in the general case: x_A needs to be low enough such that B's profit is at least zero. Solving this quadratic equation gives the two x_A^{det} that can deter the entry of firm B, whereas only the higher one is economically meaningful since the other is always negative:

$$x^{det}_{A,1,2} = -d \pm \frac{1}{\gamma}\sqrt{f\gamma(9\gamma-8)}$$
$$\Rightarrow x^{det}_{A} = \underbrace{-d}_{negative} + \underbrace{\frac{1}{\gamma}\sqrt{f\gamma(9\gamma-8)}}_{positive} \tag{97}$$

If $|-d| < \frac{1}{\gamma}\sqrt{(f\gamma(9\gamma-8)}$ there exists a positive amount of R&D output that deters B's entrance and shows the case of under-investment as a result of a potential entrant, which implies for f: $f^{det}_{l} > \frac{d^2\gamma}{9\gamma-8}$. This is the same lower bound as in the general case, where the reason for this equality was already pointed out (see 3.4.2). For $\gamma = 3$ and $d = 30$ this lower bound is 142.11. Clearly there must be a minimum fixed entrance cost otherwise firm B would always enter. For all $f < 142.11$ entry deterrence is not an option for firm A. Additionally, like in the general case, two more interval boundaries are of interest. The first one is defined by $x^{det}_{A} < x^{SA}_{A}$ (entry deterrence (SA)). x^{SA}_{A} is calculated in (85). Setting up the inequality and solving for f gives the upper boundary f^{det}_{u}. Continuing using the stated parameter leads to $f^{det}_{u} = 229.34$. Putting both conditions together yields the first range of f

$$\frac{d^2\gamma}{9\gamma-8} < f < \frac{4d^2\gamma(9\gamma-8)(9\gamma^2-8\gamma)^2}{(-128+368\gamma-405\gamma^2+162\gamma^3)^2} \tag{98}$$

in which entry deterrence is possible. Here, for all f bigger than 142.11 but smaller than 229.34, firm A can keep B out of the market by investing a lower amount into R&D than under the standard Stackelberg game. If, for example, $f = 200$, the basic game would give $x^{SA}_{A} = 8.11$. Using equation (97) yields a lower deterrence investment of $x^{det}_{A} = 5.59$. Those investments lead to $\pi^{SA}_{A} = 165.01$ and $\pi^{det}_{A} = 386.46$, respectively. In this case, the profit-maximizing firm A would strategically under-invest to keep the potential entrant B out of the market. For all $f \geq 229.34$, the entrance deterring R&D investment is higher than x^{SA}_{A}. As described earlier, this is not strategic over-investment but strategic under-investment from a different point of view.

Since the fixed cost is high enough to keep the potential entrant out of the market, firm A wants to behave as a monopolist and invest x^M, which is 15 in our example. But due to the spillover effect, the profit of firm B is getting higher the more firm A is investing, since B's unit production costs decrease in x_A such that a positive profit can be gained despite $f > 229.34$. As a consequence, firm A under-invests compared to the monopoly amount until $f = f^{blo}$, where it immediately switches to x^M. Thus, the second interval that provides under-investment (entry deterrence (M)) is

$$\frac{4d^2\gamma(9\gamma-8)(9\gamma^2-8\gamma)^2}{(-128+368\gamma-405\gamma^2+162\gamma^3)^2} < f < \frac{d^2\gamma^3}{(\gamma-1)^2(9\gamma-8)}. \tag{99}$$

To give an example, f is set equal to 300. Again, $x_A^{SA} = 8.11$ and $x^M = 15$ but now $x_A^{det} = 13.59$. Firm A's profit if it invests the monopoly amount would be $\pi^M = 9.01$, which is much less than $\pi_A^{det} = 373.01$ such that firm A would deter B's entry.

A version of the graphical overview (2) for $\beta = 1$, $\gamma = 3$ and $d = 30$ can be found in the appendix (3). The next section continues with the numerical interpretation of an accommodated entry.

4.2.3 Accommodated entry

Evidently, the fixed entrance cost f plays an important role in the Stackelberg-Spence-Dixit interpretation. If $f \geq f^{blo}$, the incumbent firm can keep the other firm out of the market with no effort. In the intervals determined above, reducing the R&D investment on its deterrence level is favorable. In addition, a low level of f implies that entrance deterrence becomes very costly or even unprofitable. In the latter case, firm A consequently plays accommodated entry and admits firm B's entrance.

Since the calculation for the general model is getting too complex, it is shown in more detail here. Starting point builds assumption (68). For $\beta = 1$ it reads

$$\frac{f}{2}(15-\frac{8}{\gamma}-9\gamma)+\frac{d}{2}(-d\gamma+2\sqrt{f\gamma(9\gamma-8)}) \leq \frac{d^2\gamma(128+3\gamma(39\gamma-80))}{2\gamma(368+81\gamma(2\gamma-5))-256}-f. \tag{100}$$

Solving for f after applying $d = 30$ and $\gamma = 3$ gives

$$f^{acc}_{1,2} = \frac{2430(983 \pm 3\sqrt{49445})}{6479}, \tag{101}$$

which are approximately $f^{acc}_1 = 118.49$ and $f^{acc}_2 = 618.88$. Without yet considering if those results make economically sense, the incumbent firm would play accommodated entry for all values of f that are smaller than f^{acc}_1, deterrence in the range of $f^{acc}_1 < f < f^{acc}_2$ and again accommodated entry for all $f > f^{acc}_2$. The first range is consistent since $f^{acc}_1 < f^{det}_l$. Firm A could only deter B's entry by investing a negative amount of R&D so it has to play accommodated entry anyway. In the case of $f^{acc}_1 = 118.49$, the deterrence investment would be $x^{det}_A = -2.61$. This implies for all $f^{acc}_1 < f^{det}_l$ that firm A cannot play deterrence although it would be more beneficial. This is not possible which is why f^{acc}_1 can be rejected. Firm A plays accommodated entry as long as f is not large enough to deter firm B's entrance and switches to x^{det}_A once $f > f^{det}_l$. One could suggest that if negative R&D investments are not an option, firm A could at least set $x_A = 0$ for all $f^{acc}_1 < f < f^{det}_l$. If, to prove otherwise, the fixed costs are, for instance, 130, $\pi^{acc}_A = 235.01$ whereas $\pi^{SA}_A(x_A = 0) = 157.30$. The second critical value f^{acc}_2 can also be rejected. As shown in the section above, just as f exceeds f^{blo}, the first-mover can blockade the other firms entry and stays monopolist. Hence there is no need to depart from the first best optimal R&D investment and play accommodated entry.[27] To sum up, if entrance deterrence is possible, the first-mover will always choose this option. When f is large enough to blockade the followers entry, the incumbent acts like a monopolist. Only if f is too small, accommodated entry is played.

[27]Besides, the fixed costs f^{acc}_2 induce negative profits π^{det} and π^{acc} such that both firms want enter.

4.3 Game theoretical analysis and policy implications

The preceding sections have analytically shown under-investment for purpose of entrance deterrence. Some empirical investigations are in line with this result by revealing under-investment, but this cannot directly be assigned to strategic behavior like building a barrier to entry. Margolis and Kammen (1999) identified under-investment in the US energy sector compared to other sectors by using federal and private R&D investments and patent records from the years 1976 to 1996. Kim et al. (2012) empirically examines the impacts of entry liberalization on the basis of panel data of 70 electricity-generating firms and find that "entry liberalization is associated with a decline of R&D investment" (Kim et al. 2012, p. 111). They name bunch of reasons including spillovers. In a more recent study, Bjorner and Mackenhauer (2013) reject that there are more spillovers within the renewable energy research compared to other types of private research in Denmark on basis of private company panel data from 2000 - 2007.

Although the reason for the precompetitive stage is primarily to remove uncertainty when it comes to the investment decisions, the static game additionally allows getting more information about the relevance of under-investment as an entrance barrier. Tesoriere (2008) used the preplay stage to find a subgame-perfect Nash equilibrium in case of ex-ante identical firms and endogenous timing. He states that a sequential play can only be a subgame perfect Nash equilibrium if leader and follower are better off than in the simultaneous timing, otherwise at least one of them could do better by taking the same timing decision as the rival. Since there does not exist a spillover rate that could lead to this, only the simultaneous entry in period one can become a subgame perfect Nash equilibrium. As one will see in this section, a similar conclusion can be drawn here. To predict the firms' decisions in the precompetitive stage the payoff functions for every possible strategy profile are necessary, which are the profits the firms make by each timing constellation. All numerical results for $\beta = 1$, $\gamma = 3$, $d = 30$ and the illustrative example values for f can be found in the appendix (tables (1) - (4)).

A firm in the present model trades-off the first-mover advantage against the latecomer's benefits. Entering the market in the first period enables the firm to sell the good in two periods in contrast to only one for entry in period two. Additionally, if the rival decides to move late, the firm becomes Stackelberg leader in R&D investments and monopolist in the first trading period. On the other hand, a fraction of this cost reducing R&D investments spills over to the latecomer whose competitiveness and therewith profitability increases. The Stackelberg leader tries to lower the drawback from the positive externality by strategic investment. Intuitively, Stackelberg leadership is more attractive for small spillovers, whereas the opposite applies to the follower. Furthermore, high fixed entry cost would make an early entry more likely since this means more time to recoup the investment.[28]

One ascertains that in the game (C2) only negative profits appear, since profit for the assumed parameters before subtracting the fixed cost is 96.98 and the lowest f considered here is 100. Of cause the firms would not enter in this case so that profit would be zero but for clarification the profits left as they stand. (C2) will never be superior to (C1), (SA) and (SB), since no spillovers occur and the firms are only for one period active. As in Tesoriere (2008), (SA) and (SB) are a subgame perfect Nash equilibrium if both, first and the second moving firm can make a higher profit than under the simultaneous entry in period one. In the first three intervals for f, early entry is the strictly dominant strategy for both players such that game (C1) is played. For all f bigger f_l^{det} the entry of a second moving firm is deterred or blockaded by the under-investment of the first-mover such that the profit of the follower is zero. Generally, both firms would like to be the Stackelberg leader, but since the profit of being the follower is less compared to the profit in (C1), the sequential game would not appear in this model framework. For a very high fixed entry cost (as in our example $f = 400$) simultaneous entry in period one is not beneficial anymore, as the entrant's profits are insuffi-

[28]The entry timing is widely discussed in the literature. For an overview about the determinants that influence the incentives to be a pioneer or a follower see Lilien and Yoon (1990). Advantages and disadvantages are discussed in Lieberman and Montomery (1988). Nehrt (1996) empirically investigates if a first-mover advantage in environmental investments exists.

cient to cover the costs, such that both firms decide to stay out of the market although one firm could still make positive profits.

A full welfare analysis is out of the scope of the paper, but a short outlook with corresponding policy recommendations is given here. The aim of a social planer is to maximize the overall welfare, which consists of the sum of consumer surplus and industry profit. By now it has become clear that the strategic position the firms will choose heavily depend on f. The same holds for the welfare implication. Like described above, the firms do not enter if they would gain negative profits, such that also no consumer surplus accrues. Considering the game as a whole, the firms act welfare optimal in case of moderate fixed cost by entering early, such that under-investment for entry deterrence will not emerge. Thus, we can recommend policy makers to support low administrative and financial entry barriers in order to enable early entry for all firms. The market failure that still arises in this case is due to not internalized positive R&D spillovers like shown in D'Aspremont and Jaquemin (1988). Policy measures to encourage the firms to undertake R&D are, for instance, subsidies or technology-push policies like portfolio standards.[29] For large fixed entry costs, however, it is welfare improving to coordinate entry such that one firm enters.

Looking on the sequential game separately completes the welfare analysis. That implies that the roles of the firms are assigned exogenously, such that one firm has the R&D leadership and the other firm follows. For all $f_l^{det} < f < f_u^{det}$ the first-mover can prevent the market access of the second moving firm by under-investing. As a consequence, the market is less competitive, the produced output is lower und prices are higher. The above state common policy measures to overcome under-investment can be used here too. Additionally, particular care is required in case of public research assignments. Those are often contracted to initiate an industry to move in a

[29]Publications that examine appropriate policy measures to support R&D in renewable energies are e.g. Hinloopen (1997, 2000) or Menanteau et al. (2003). Braun et al. (2010) find empirical evidence that public R&D stimulates innovation, particularly in solar technology.

certain direction or to start a new field of research if the private economy does not undertake R&D because of reasons like uncertainty (Popp et al. 2009). To overcome the market failure that firms under-invest to stay monopolist instead of getting and diffusing new technology, government-industry partnerships should carefully be designed.

5 Conclusion

The purpose of this paper is to show if under-investment in R&D can be used to deter the entry of a rival. To know more about the political relevance of this market failure, the case of sequential entry is embedded in a static game of complete information, where two firms decide to move in the first or second period. Three games can arise as a result: Both firms invest and enter simultaneously in period one, period two, or sequentially. If the latter occurs, the first-mover can try to gain the monopoly position by strategic investment. This behavior is analyzed on basis of Tirole's (1994) Stackelberg-Spence-Dixit model. Depending on the fixed entry cost, the first-moving firm can blockade and deter the followers entry, or has to accommodate the entry. Interestingly, two intervals for the entry deterrence case arise. For moderate fixed costs, under-investment can be found, contrasting the equilibrium Stackelberg R&D outcome. If the fixed costs reach a value such that the potential entrant can only enter the market if there is sufficient knowledge spillover, under-investment towards the monopoly R&D amount arises. However, the firms make the timing decision in a precompetitive stage, knowing the following payoff matrix given the fixed entry cost, such that the only subgame perfect equilibrium is simultaneous entry in period one. The thereby arising market failure is just due to the not internalized positive effect of the R&D spillover, which is not part of this paper but a wide range of previous literature, where policy measures to overcome this externality can be found.

Based on this model, entry deterrence by R&D under-investment does not appear as long as an early market entry is possible for all firms. Therefore it is necessary to lower administrative or financial entry barriers. Abstracting the Stackelberg game from the basic setting yields another policy recommendation: Government R&D funding and government-industry partnerships should carefully be designed such that the supported firm can not try to deter follower's entry by intentional under-investment.

It would be interesting to see how the results change if additionally one part of the fixed entry costs decreases by investing into R&D such that waiting is getting more attractive. As a possible result it could appear, that both firms want to be the follower such that at the end no spillovers will be generated - a classical prisoner's dilemma with severe consequences for welfare. One-way spillovers that just develop for sequential market entry could have a similar effect. Accordingly, further research on this topic is needed. Aside from that, a detailed welfare analysis on this field is missing as yet but should be supplemented.

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Appendix

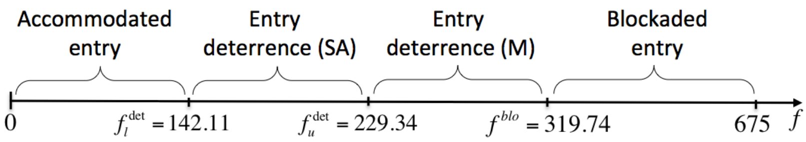

Figure 3: Strategic options conditional on the fixed market entry cost for the numerical example

Table 1: Payoff matrix: Profits for $f < f_l^{det}$, numerical example for $f = 100$

$f < f_l^{det}$ $f = 100$		Firm B	
		F	S
Firm A	F	204.71; 204.71	265.01; 129.32
	S	129.32; 265.01	−3.02; −3.02

Table 2: Payoff matrix: Profits for $f_l^{det} < f < f_u^{det}$, numerical example for $f = 200$

$f_l^{det} < f < f_u^{det}$ $f = 200$		Firm B	
		F	S
Firm A	F	104.71; 104.71	386.46; 0
	S	0; 386.46	−103.02; −103.02

Table 3: Payoff matrix: Profits for $f_u^{det} < f < f^{blo}$, numerical example for $f = 300$

$f_u^{det} < f < f^{blo}$ $f = 300$		**Firm B**	
		F	S
Firm A	F	$4.71; 4.71$	$373.01; 0$
	S	$0; 373.01$	$-203.02; -203.02$

Table 4: Payoff matrix: Profits for $f^{blo} < f$, numerical example for $f = 400$

$f^{blo} < f$ $f = 400$		**Firm B**	
		F	S
Firm A	F	$-95.29; -95.29$	$275; 0$
	S	$0; 275$	$-303.02; -303.02$