Dynamic R&D Incentives with Network Externalities

Inaugural-Dissertation
zur Erlangung des Grades
Doctor oeconomiae publicae (Dr. oec. publ.)
an der Ludwig-Maximilians-Universität München

2005

vorgelegt von
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Promotionsabschlussberatung: 13. Juli 2005

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Acknowledgments

I would like to thank Prof. Stefan Mittnik, PhD. and Toker Doganoglu, PhD. for continuous guidance and support. Colleagues at the Center for Information and Network Economics at the University of Munich are still a source of motivation and encouragement.

I would also like to thank Prof. Dr. Monika Schnitzer who agreed to be my second supervisor and provided a very useful environment to exchange ideas through the internal seminars at the Seminar for Comparative Economics.

This dissertation has greatly benefited from valuable comments and suggestions obtained at internal seminars at the University of Munich, the conference of the European Association of Research in Industrial Economics (EARIE, 2004) and student presentations at the Kiel-Munich workshop on the Economics of Information and Network Industries (2003, 2004).

Generous financial assistance by Volskwagen Stiftung and the Munich Graduate School of Economics makes this research agenda possible.

Contents

Introduction

An industry exhibits network externalities when the benefit that consumers enjoy from purchasing one or several of its goods depends on the number of other consumers that use the same and/or compatible products. Prominent examples of these industries are software, telecommunications, and consumer electronics, among others. For the firms in those sectors, the presence of network externalities implies that the attractiveness of their products is a function of their quality-adjusted prices and the potential benefits attached to their expected network sizes (i.e. installed bases).[1]

The presence of network externalities has important consequences for the structure of an industry. On the demand side, the presence of network externalities indicates that any decision made by a consumer inside the industry is directly related to the consumption decisions made by other consumers of the same industry. In other words, consumers *must* form expectations about the current and future evolution of the competing installed bases before acquiring a network good. Anticipating the best future network is a key consideration because the costs associated with switching from one network to another could be prohibitively high.

At the same time, the role of installed bases and consumers' expectations are not only crucial for consumer demand. Their impact may be even decisive in the mere future of a network industry: A network technology may dominate a market only because it is expected to do so. For example, the initial success of MS-DOS is usually attributed not to any technical superiority, but to the fact that it was supported by IBM. Once established, the attractiveness of MS-DOS kept increasing due to a growing

[1] Katz and Shapiro (1985, 1986) and Farrell and Saloner (1985, 1986) present the seminal treatments, and Katz and Shapiro (1994) and Economides (1996) present excelent surveys on network markets.

installed base. Thus, in contrast to traditional industries, the expectation formation process is crucial in the evolution of network industries and their installed bases.[2]

In addition, the particular demand structure of network markets has important implication on the supply side. Firms' strategic decisions are affected because the value of a technology is related to a network externality and the implied network benefit it provides. In other words, a producer of a network good *cannot* fully control the overall quality of the product he offers. Given that the surplus provided by a network good is a function of the pattern of adoption exhibited in the market, firms' strategies are aimed at coordinating consumers' actions in favor of their goods.

Several studies have shown how pricing considerations, as well as compatibility, entry and investment decisions are affected by the presence of network externalities.[3] For instance, Grindley (1995) states that due to the presence of network externalities, firms in network industries follow very different rules from those observed in traditional industries. While the producer of a new product in a conventional market tends to place it on the market early, differentiate the good as much as possible, protect it from imitation and charge high prices, successful producers of network goods have often done the exact opposite.

According to Grindley (1995), casual observation of the evolution of network industries such as video cassette recorders, personal computers, digital audio standards and high-definition television, among others, suggests that the main objective of successful firms was to build quickly an installed base. This, in some cases, implied holding back the product launch until all the obvious flaws were corrected, encouraging other manufacturers to adopt the same standard design, and lowering prices to maximize early sales.

[2]In fact, among some authors, Besen and Farrell (1994), Katz and Shapiro (1994) and Arthur (2000) have pointed out that it is the role of consumer expectations what determines the particular dynamics in industries with network externalities, in comparison with other industries under increasing returns to scale. Not without reason, these particularities on the demand side have led the analysis of network externalities to be also referred in the literature as demand scale economies, increasing returns to adoption, network effects, network economies and positive feedback, among others.

[3]See, for example, Gabel (1991), Besen and Farrell (1994), Katz and Shapiro (1994), Grindley (1995) and Shapiro and Varian (1999) for general analyses of the impact of network externalities on firms' strategies.

Interestingly, all these cases shared a common feature: Because of the existence of installed bases and the implied necessity to build and sustain such bases, competing firms displayed an intense rivalry, along with fierce technological competition. In fact, rapid technological progress derived from R&D competition is a common observation in many industries with network externalities. Technological innovations allow rivalling firms to introduce new products like interactive TV, Digital Versatile Disk (DVD), and digital imaging. Moreover, in nascent industries, extensive investments in R&D are usually required to introduce new standards or dominant designs.

In spite of its relevance, the economic literature on R&D and technology choice in industries that exhibit network externalities is still in its early stage of development. Particularly, the determinants of private innovative incentives and the conditions under which misalignments with the social incentives arise, is an area of research that has not received enough attention. This dissertation is a step in that direction.

Specifically, the work presented in this volume aims at contributing to two main points identified but not fully exploited in the existing literature. First, in its great majority, the current literature takes the process of R&D as exogenously given and analyzes the conditions under which an innovation is adopted. Second, most of the work devoted to the analysis of investment decisions with network externalities considers situations where the entrant arrives with a (exogenously given) new technology, without considering a strategic response by the incumbent to the threat of entry.[4]

This dissertation presents three self contained essays focused on the incentives to carry out uncertain R&D processes in the presence of network externalities, and the potential difference that may arise in comparison with the social optimum.

In the literature on network markets, there has been a widespread concern about the impact of installed bases on social welfare. In particular, it has been argued that in the presence of network externalities, it is excessively difficult for firms to enter the market with new products or technologies that lack an installed base of past consumers. The focus of the concern is that usually the new technology is of better quality and the

[4]See Farrell and Saloner (1985, 1986), Katz and Shapiro (1986, 1992), De Bijil and Goyal (1995), Shy (1996), and Fudenberg and Tirole (2000), among others.

society would be better off if that technology is adopted. However, due to the presence of an installed base, the new technology may not be adopted. This market inefficiency has been termed in the literature as excess inertia.

Excess inertia arises because in equilibrium, the absence of an installed base may make consumers too reluctant to adopt the new technology. For instance, old consumers may perceive that important network benefits could be lost due to expectations of low mass of current consumer changing to the new technology. Analogously, new consumers may prefer to enjoy the network benefits attached to an established installed base. In the literature, some authors have provided the theoretical rationale for this phenomenon (Farrell and Saloner 1985, 1986).

Furthermore, the opposite inefficiency is also possible. Even if the market adopts the new, better emerging technology, under some specific conditions overall social welfare would be higher if consumers stay with the old one. This situation may arise when, for instance, a considerable proportion of old consumers are not able to change technology. Another common situation that exemplify this type of inefficiency is when an influential consumer (i.e. a government) induces a new technology (i.e. a software) forcing other consumers to follow suit. This inefficiency has been termed as excess momentum (or insufficient friction) and has been repeatedly put forward in the literature (Katz and Shapiro 1992, 1994).

Chapter 1 departs from existing literature and analyzes the efficiency of the market outcome (i.e. whether private incentives match social ones) for the case of endogenous and uncertain R&D processes. In particular, the main objective is to investigate under which conditions private incentives to innovate tend to exhibit excess inertia or excess momentum. The chapter presents a simplified two-period duopoly model of competition with uncertain technological progress, in order to determine and compare the private and social incentives to innovate.

The chapter considers an incumbent firm with an installed base and a potential entrant. Both firms may develop a new technology and, after the outcome of the innovation process is realized, compete in prices only once. The analysis is related to previous work by Kristiansen (1996) and Choi (1994), where an incumbent and a potential entrant must choose the risk associated with an R&D project aimed at developing a new network good. Both papers analyze the social efficiency of the R&D projects and conclude that the presence of network externalities imply inefficiencies. However, Choi (1994) does not consider the case of a strategic response by the incumbent firm and Kristiansen (1996) present opposite results compare to the ones presented in chapter 1.

The chapter presents four main results. First, for low cost of innovation entry does not occur at all and for high cost of innovating, entry occurs with positive probability. Low cost of innovation implies that through investments the incumbent firm is able to preempt the entrant. Second, when entry takes place the incumbent invests always more than the entrant and, therefore, there is a high probability that the incumbent maintains its monopoly position. This result implies, that even though the incumbent has an advantage to keep monopolizing the market, is being force to innovate given the threat of entry. Third, contrary to Kristiansen (1996), from a welfare perspective the incumbent investment level is too low and the entrant investment level is too high. That is, the industry exhibits excess momentum. This result is due to the existence of locked-in consumers and states that the new technology is adopted too often in comparison to what it would be socially optimal. Finally, and fourth, the inefficiency observed in the private outcome is solely due to the presence of network externalities.

The critical assumptions leading to the results presented in chapter 1 are that the network goods are durable, consumers buy only once and the behavior of initial consumers (i.e. installed base) is totally exogenous. In other words, initial consumers get always locked-in and use the same good over their two periods of life. Even though the assumption of unitary inelastic demands has been considered in almost the entire literature on network externalities, durability and the possibility of making different purchases are common features in network markets.[5] For example, consumers of software find optimal to upgrade their current versions even thought they are still functional. The analysis of durability and repeated purchases under network externalities

[5]See Katz and Shapiro (1999) for an informal analysis of antitrust in software markets, where these two characteristics, durability and technological progress are explicitly considered.

and endogenous R&D incentives is presented in chapter 2.

The analysis of R&D incentives and durability is a complex one and it has not been sufficiently examined in the economic literature. In essence, the problem is as follows. R&D incentives are aimed at improving future goods, either by enhancing their quality or by reducing their production costs. However, in the presence of durable goods, a future better good reduces the future value of current and past produced goods. This reduces current consumers' willingness to pay because they foresee that in the future their good is of lower quality (or price) in comparison to the one that will be available in the future. Therefore, and under some conditions, without explicit commitment on the R&D efforts, a firm may reduce its overall profits by undertaking too much R&D initiatives.

For the case of network externalities, the durability problem has been already analyzed in the literature. However, this is not the case under endogenous R&D incentives. Ellison and Fudenberg (2000) consider the case of the introduction of a new network good (i.e. software) and consider explicitly the role of durability. They show that a monopolist firm may actually face a commitment problem and introduce the new good in cases where overall profits would be higher if the firm does not introduce it. The reason for that result is that, by only considering period 2 profits, the monopolist does not internalize the negative impact that introducing a new good in period 2 has on the price charged in period 1. In their two-period model, there is only a monopolist with an exogenously produced network good with a given quality in period 1 and the possibility of introduce a product with better quality in period 2.

Chapter 2 presents a model that extends that of Ellison and Fudenberg (2000) by introducing and endogenous R&D process in the production of the new technology, and considers the role of a potential entrant. The chapter shows results not present in the Ellison and Fudenberg (2000) analysis. In particular, the chapter considers a two-period framework with an incumbent, a potential entrant and an inflow of new consumers. Consumers are homogeneous and participate in a market with durable network goods. Conditional on uncertain R&D efforts, the firms may introduce a better network good in period 2. As in chapter 1, the analysis takes into account the private, as well as the social incentives to innovate in order to check the market efficiency.

The chapter presents three main results. First, the threat of entry reverses the commitment problem that a monopolist (without such threat) may face in its R&D decision given the durability of the network goods. This result is not present in the current literature and follows from the role that R&D incentives play in deterring entry. In our case, the monopolist's commitment problem arises only due to the presence of network externalities.

Second, the levels of R&D determined by market outcome might differ from the socially optimal levels. In particular, a potential entrant always over-invests (as an entry strategy) and an established incumbent might exhibit higher, lower or equal R&D levels in comparison with the social optimum. This result suggests that successful entry takes place too often in comparison with the social optimum (i.e. excess momentum).

And third, the extent of network externalities is the crucial parameter in the efficiency of the incumbent R&D level. In fact, it is only the presence of network externalities that permits, potentially, to the established incumbent to provide an efficient level of innovation. Without network externalities (or very low network effects), it is shown that the incumbent firm always under-invests in R&D efforts. This result sheds some light on the debate whether a dominant incumbent in a network industry provides sufficient innovation to the society.

Chapter 1 and chapter 2 present results embedded in two-period models. These models extend the current literature by highlighting the mechanism behind the incentives to pursue R&D initiatives in network industries, and are simple enough to provide a clear intuition of their results. Chapter 3 builds on the intuition and the results of the previous two chapters but takes the analysis one step further by considering the evolution of a network industry in a fully dynamic setup.

Introducing dynamics is a natural step for two main reasons. First, the process of invention and introduction of new technologies is a continuous process that benefits from previous developments. In network industries, this is particulary important given the rapid technological progress observed, and the associated strategic role of R&D

investments. And second, by allowing the model to be independent of initial and end effects, the robustness of the results in the literature can be verified and a richer description of the incentives behind an innovation effort can be obtained.

Chapter 3 analyses the case of a dynamic duopoly model of quality competition in the presence of network externalities. The methodology utilized adapts the Markov-perfect equilibrium framework presented in Ericson and Pakes (1995) to track the evolution of an industry. In particular, the model considers two firms (an established firm and a challenger) that compete each period with two incompatible technologies over an infinite horizon. To capture the role of the installed base, the model considers overlapping generations of homogeneous consumers that live for two periods and make purchases (inelastically) only once when they arrive to the market.

In order to analyze the incentives to innovate, the model considers the case of endogenous and stochastic R&D incentives, allowing for the case of technological competition outside the industry. The model is solved in two steps. In the first step, the product market competition observed in each period is determined given suitable assumptions. For any given quality state, the equilibrium prices and per-period profits are computed as a function of the investment levels. In the second step, given these equilibrium prices and the corresponding per-period profits, the fully dynamic investment decision problem is stated and solved numerically using the aforementioned approach and the computational algorithm developed in Pakes and McGuire (1994).

This methodology permits a detailed analysis of the investment behavior of the industry. Specifically, the chapter shows four main results. First, the presence of network externalities generates incentives to invest in R&D in order to innovate. This investment levels are higher than the levels that would be observed without network externalities. This result has three important implications: i) with a positive probability, the traditional result of "monopolization" in one network technology can be overcome, resembling the industry evolution of temporary monopolists; ii) the threat of losing the market induces the established firm to follow R&D projects in order to reduce the probability of being overtaken by the challenger; and iii) the challenger has enough incentives to try to overtake the market.

Second, for high network effects, a high level of outside competition implies higher investment levels. This result implies that the relation between innovation incentives and the level of competition is not an U-shaped function, as traditional innovation theory for non-network industries suggests, but is a monotone increasing function. This result says that the expectation of exhibiting future installed bases is so strong, that even considering the case of being a technological laggard, higher investment levels are, on expectation, worth pursuing. In addition, this result rationalizes the observed high technological competition in network industries.

Third, the chapter shows that the market tends to over-invest in R&D in comparison with the level that maximizes social surplus. In line with current literature, this result implies that introduction of new incompatible technologies occurs too often in equilibrium. However, the result is obtained for the case of endogenous R&D incentives in a fully dynamic framework.

And fourth, with high competition outside the industry, the extent of network externalities is critical in determining the size of the inefficiency associated with the investment levels. This result shows that in the presence of high outside R&D competition, the inefficiency associated with the investment level is minimal when network externalities are not present. As network effects become more important, the inefficiency is increased monotonically. This result permits to see a clear impact of the role of network externalities in determining innovation incentives and the associated social efficiency.

Chapter 1

R&D Incentives in Network Industries

1.1 Introduction

An industry exhibits network externalities when the benefit that consumers enjoy from purchasing one or several of its goods depends on the number of other consumers that use the same and/or compatible products. For the firms in those sectors (e.g. telecommunications, consumer electronics, operating systems, etc.), the presence of network externalities implies that the attractiveness of their products is a function of their quality-adjusted prices and the potential benefit attached to their expected network sizes (i.e. installed bases).[1]

Several studies have shown how pricing considerations, as well as compatibility, entry and investment decisions are affected by the presence of network externalities.[2] Moreover, due to the presence of these externalities, firms in network industries might even follow very different rules from those observed in traditional industries.[3]

[1] Katz and Shapiro (1985, 1986) and Farrell and Saloner (1985, 1986) present the seminal treatments, and Katz and Shapiro (1994) and Economides (1996) present excelent surveys on network markets.

[2] See, for example, Gabel (1991), Besen and Farrell (1994), Katz and Shapiro (1994), Grindley (1995) and Shapiro and Varian (1999) for general analyses of the impact of network externalities on firms' strategies.

[3] While the producer of a new product in a conventional market tends to place it on the market early, differentiate the good as much as possible, protect it from imitation and charge high prices,

This chapter analyzes how network externalities influence industry Research and Development (R&D) incentives when two network technologies compete. The chapter focuses on the levels of R&D investments, the social efficiency of those efforts and the role of networks' compatibility.

Rapid technological progress derived from R&D competition is a common observation in many industries with network externalities. Technological innovations allow rivalling firms to introduce new products like interactive TV, Digital Versatile Disk (DVD), and digital imaging. In nascent industries, extensive investments in R&D are usually required to introduce new standards or dominant designs.

However, the literature on R&D and technology choice in industries that exhibit network externalities is still in its early stage of development. The existing literature, in its great majority, takes the process of R&D as exogenously given and analyzes the conditions under which a new innovation is adopted (Farrell and Saloner (1985, 1986), Katz and Shapiro (1986, 1992), De Bijil and Goyal (1995), Shy (1996), Fudenberg and Tirole (2000), among others). Moreover, most of the work devoted to the analysis of adoption of new technologies with network externalities considers situations where the entrant arrives with a (exogenously given) new technology, without considering a strategic response by the incumbent to the threat of entry.[4]

This chapter proposes a simplified two-period duopoly model of competition with uncertain technological progress, in order to determine the private incentives to invest in R&D. The model is simple enough to be able to isolate the main forces behind the incentives to innovate and the role of network externalities. Specifically, we consider an incumbent firm with an installed base and a potential entrant that challenge the incumbent only once. We assume a uncertain technological progress. In particular, by investing in R&D before price competition takes place, each firm can influence the probability of developing a better technology to compete with.

We also consider the social incentives to innovate and compare the results with the market outcome. We show the conditions under which potential inefficiencies arise and

successful producers of network goods have often done the exact opposite. See Grindley (1995).

[4]Some exceptions that will be discussed below include Kristiansen (1996, 1998).

propose, with our model, an explanation to these inefficiencies. Finally, we consider the role of compatibility choice and its impact on the R&D incentives.

We present four main results. First, for low cost of innovation entry does not occur at all and for high cost of innovation, entry occurs with positive probability. Low cost of innovation implies that through investments the incumbent firm is able to preempt the entrant. Second, when entry is possible, the incumbent invests always more that the entrant and, therefore, there is a high probability that the incumbent maintains its monopoly position. This result implies that, even though the incumbent has an advantage to keep monopolizing the market, he is forced to innovate given the threat of entry. Third, from a welfare perspective, the incumbent invests too little and the entrant invests too much given the existence of locked-in consumers. These results are solely due to the presence of network externalities and are in contrast with the results reported in Kristiansen (1996). Fourth, by choosing to produce compatible products, firms do not necessarily reduce the R&D competition intensity as has been suggested for example in Katz and Ordover (1990) and Kristiansen (1998). Moreover, for high cost of innovation compatibility may even increase the pace of innovation observed in the industry.

Even though our model is related to the literature on network externalities, the modelling strategy, as well as some results, differ with existing analyses. For instance, Kristiansen (1996) also analyzes endogenous and uncertain technological process in a network industry. He presents a model to describe how firms, an incumbent and a potential entrant, choose among different R&D projects to develop a new incompatible technology. In particular, he discusses the firms' choices of R&D projects in terms of the risk associated to each of them. To isolate the role of the riskiness of such projects, Kristiansen (1996) assumes a mean-preserving spread criterion in the R&D technology. That is, even though riskier projects exhibit higher returns and lower probability of success, the expected value of all R&D projects is the same.

Particularly, he finds that from a social welfare point of view, the incumbent chooses a too risky and the entrant a too certain R&D project. This inefficiency arises because of the existence of an installed base of locked-in consumers of the incumbent's technology that is not taken into account when the firms decide on the R&D projects. The entrant chooses a too low risk project because it exhibits a high probability of success (i.e. entry) but, if successful, his R&D project provides a too low value for the society. The incumbent chooses a too risky project because, if successful, it can extract high consumer surplus. However, his choice does not internalize the potential welfare loss of the locked-in consumers in the case of successful entry by a firm with an incompatible technology.

As in Dasgupta and Maskin (1987), Kristiansen (1996) adopts the additional assumption that riskier R&D projects entail unambiguously higher costs of development. Although plausible, this assumption implies for his results that the incumbent firm invests too much and the entrant firm too little in comparison with the social optimum. We believe that in network industries the opposite phenomenon is commonly observed. Namely, entrants usually tend to heavily (over) invest in R&D in order to introduce new network incompatible technologies (e.g. interactive TV, Compact Disk (CD), Digital Versatile Disk (DVD), and digital imaging). We propose a model where this is the case. In addition, Kristiansen (1996) shows, as in our model, that the differences between private and socially optimal R&D initiatives are due to the presence of network externalities.

In a similar paper, Choi (1994) studies an entrant's choice among R&D projects with different risks in a two period model in which consumer can delay adoption. As in Kristiansen (1996), Choi (1994) also considers the case of mean-preserving spread criterion in the R&D technology. In his model, the quality of the incumbent technology is constant over the two periods, while the entrant's technology evolves stochastically. By choosing a level of risk, the entrant firm may affect the distribution of the quality of its good to be introduced in the second period. Two buyers enter sequentially in each period. The first buyer can observe the R&D project (i.e. risk choice) of the potential entrant and may decide to wait until the second period to make a purchase. Choi (1994) concludes that the first buyer may adopt a technology too early in relation with the social optimum. In addition, similar to Kristiansen (1996), the paper shows that the potential entrant chooses a low level of risk in comparison with the level that maximizes social welfare. However, Choi (1994) does not consider the costs associated with the selection of the R&D projects, which are an important dimension of the incentives to innovate. We also depart from his work by considering the strategic role of the R&D decision by the incumbent firm.

In a more recent work, Kristiansen (1998) studies the decisions of entry and compatibility in a duopoly market in the presence of network externalities. R&D incentives are endogenous in the sense that an earlier entry decision imply higher costs. However, this extra cost does not affect the probability distribution of the quality of the network goods and represents more closely a sunk entry cost rather than a uncertain R&D investment. Kristiansen (1998) shows that when the firms choose to produce compatible goods, it is optimal for them to introduce their goods later, and therefore compatibility reduces the R&D competition intensity observed by the two firms. We present the opposite result in a model where investments in R&D do affect the probability distribution of the quality of the network goods.

The chapter is organized as follows. In section 2 we present the model. In section 3 we analyze the market equilibrium that determines the private incentives to innovate. In section 4 we present the socially optimal outcome and compare it with the results of section 3. Section 4 consider the role of compatibility. Section 5 concludes.

1.2 The Model

Consider a two-period model of an industry that exhibits network externalities. In period 1 there is an incumbent monopolist, I, that produces a network good associated with a quality level q_1. The incumbent monopolist serves the entire market in this period and builds an installed base. Between periods 1 and 2, the incumbent can invest in a potential innovation, which will enable him to achieve, with probability s_I, a higher quality level q_2 for the good he produces in period 2. We denote this quality improvement as $q_2 - q_1 = q_\Delta > 0$. For the cases when the innovation is not achieved, event that occurs with probability $1 - s_I$, the incumbent produces in period 2 the same good it produced in period 1. The cost of this investment increases with the probability of achieving the innovation and is assumed to be quadratic and given by $ks_I^2/2$.

Furthermore, we introduce a potential entrant, E, who can also invest in innovation and enter the market with a network good in period 2. As the incumbent, the cost of the investment for the entrant is given by $ks_E^2/2$, where s_E is the probability that the entrant develops the innovation and enters the market with a good of quality q_2. It is assumed that in the case that the entrant does not achieve the innovation, event that occurs with probability $1 - s_E$, it is able to "copy" the technology used by the incumbent in period 1. For simplicity, it is assumed that the problem of both firms reduces to choose the probability s_I and s_E that the innovation is achieved in period 2.

On the demand side, it is assumed that each period a group of homogeneous consumer of size 1 arrives in the market. Given consumer homogeneity, we can assume without loss of generality that in each period only one consumer arrives in the market. In the model, each consumer exhibit an inelastic demand for a single unit of a network good and purchases as soon as he arrives in the market. There is no discounting. In particular, the per-period utility that a consumer derives from a network good is given by $q + bx$ where q is the quality of the good (i.e. stand-alone value), and b is the extent of the network benefit attached to the good given that the number of consumers buying the same (or a compatible) good is x.

The timing of the model is as follows. At the beginning of period 1, the incumbent produces a network good with quality q_1, sets a price and the first consumer buys. Between periods 1 and 2, the incumbent invests in order to improve its good. At the same time, a potential entrant invests in order to enter the market with an improved good. At the beginning of period 2, the outcome of the innovation is realized, price competition takes place, the new consumer arrives in the market and decides on its preferred good.

1.3 Market Equilibrium

In order to characterize the subgame-perfect equilibria in this game we proceed backwards. We start with the pricing and consumption decision in period 2.

1.3.1 Second Period Sales

In the second period firms decide on the price they charge, and the second consumer decides on the good he prefers. However, these two decisions are affected by first period purchases and the outcome of the innovation process. Recall that in period 1 the incumbent firm monopolizes the market and is able to serve it completely. The evolution of the first period is assumed exogenous. Therefore, an installed base of size 1 is built and carried into the second period. Regarding the innovation process, we distinguish among four cases; B denotes the case in which both firms innovate; I and E denote the cases in which only the incumbent or only the entrant innovates, respectively; and N denotes the history in which no firm innovates. We define four subgames Γ^B, Γ^I, Γ^E and Γ^N for each case, respectively.

In subgame Γ^B, both firm innovate and therefore are able to enter the market with a good of quality q_2. However, given the existence of an installed base, firms compete in a quality differentiated duopoly. It is further assumed that consumers are able to coordinate on the Pareto-optimal equilibrium. Therefore, they compare the maximum surplus that can be obtained from each technology and decide accordingly.[5] Thus, the benefit gross of price provided by the incumbent is equal to $q_2 + 2b$, and equal to $q_2 + b$ for the entrant. Bertrand competition implies that the incumbent's price is equal to $p_I = b$ and sells to the second consumer, while the entrant's price equals $p_E = 0$ and does not enter the market.

In subgame Γ^I, the incumbent firm innovates and sells a good of quality q_2 offering a gross benefit of $q_2 + 2b$, while the entrant provides a surplus of $q_1 + b$. Again, Bertrand competition implies an incumbent's price of $p_I = q_\Delta + b$ and sells to the second consumer, while the entrant's price equals $p_E = 0$ and does not enter the

[5] See Katz and Shapiro (1986) and Farrell and Katz (2005).

market.

In subgame Γ^E, the entrant firm is the only innovator and sells a good of quality q_2 offering a gross benefit of $q_2 + b$, while the incumbent provides a surplus of $q_1 + 2b$. In this subgame, entry takes place whenever $q_\Delta > b$. In that case, Bertrand competition implies an entrant's price of $p_E = q_\Delta - b$ and sells to the second consumer, while the incumbent's price equals $p_I = 0$.

In subgame Γ^N, no firm innovates and both offer a good of quality q_1. However, the incumbent exhibits an installed base advantage and provides a surplus equal to $q_1 + 2b$, compared to $q_1 + b$ from the entrant. Bertrand competition implies that the incumbent's price is equal to $p_I = b$ and sells to the second consumer, while the entrant's price equals $p_E = 0$ and does not enter the market.

Assumption 1 *The value of the innovation is greater than the value of the installed base.* $q_\Delta > b$.

This assumption gives the opportunity to the entrant to enter the market. That is, the value of the innovation should be able to more than compensate the network benefits provided by the incumbent firm and drives the result presented for subgame Γ^E.

We can summarize the outcome of second period price competition in the following proposition.

Proposition 1 *Given assumption 1, each second period subgame-perfect price equilibrium is unique. No entry takes place in subgames* Γ^B, Γ^I, Γ^N, *while the entrant overtakes the market in subgame* Γ^E. *Equilibrium prices are given as follows:*

i. In subgames Γ^B *and* Γ^N, $p_I = b$ *and* $p_E = 0$.

ii. In subgame Γ^I, $p_I = b + q_\Delta$ *and* $p_E = 0$.

iii. In subgame Γ^E, $p_I = 0$ *and* $p_E = q_\Delta - b$.

Proposition 1 implies that entry only occur when subgame Γ^E is realized. That is, the only opportunity for the entrant to enter the market is when it achieves the innovation and the incumbent does not.

1.3.2 First Period Investment Decisions

Given the above analysis of the period 2 play, we now solve for the subgame-perfect equilibrium of the entire game considering the optimal investment behavior of both firms.

The profit function of the incumbent is therefore given by,

$$\max_{s_I} s_I s_E b + s_I(1-s_E)(b+q_\Delta) + (1-s_I)(1-s_E)b - ks_I^2/2, \tag{1.1}$$

where k is a cost parameter.

Analogously, and following the analysis of the period 2 price competition, the profit function of the entrant is therefore given by,

$$\max_{s_E}(1-s_I)s_E(q_\Delta - b) - ks_E^2/2 \tag{1.2}$$

The first-order conditions for an interior solution are given by,

$$q_\Delta - s_E(q_\Delta - b) - ks_I^* = 0, \tag{1.3}$$

for the incumbent firm, and,

$$(1-s_I)(q_\Delta - b) - ks_E^* = 0, \tag{1.4}$$

for the entrant firm. Note that whenever the probabilities s_I and s_E are in the interval $(0,1)$, the second-order conditions are always less than zero and the investment strategies exhibit strategic substitutability. Therefore, we can find the optimal equilibrium levels by solving simultaneously equations (1.3) and (1.4) for the values of s_I and s_E. That is, the optimal investment levels are given by,

$$s_I^* = 1 - \frac{k(q_\Delta - k)}{(q_\Delta + k - b)(q_\Delta - k - b)} \tag{1.5}$$

$$s_E^* = \frac{(q_\Delta - b)(q_\Delta - k)}{(q_\Delta + k - b)(q_\Delta - k - b)} \tag{1.6}$$

We can show the following results.

Proposition 2 *Given assumption 1.*

i. For $k > q_\Delta$ there are unique values of s_I^* and s_E^* such that $0 < s_I^* < 1$ and $0 < s_E^* < 1$. $s_I^* > s_E^*$ always holds.

ii. For $k \leq q_\Delta$ the equilibrium levels of investment are unique and equal to $s_I^* = 1$ and $s_E^* = 0$.

Proof. Numeral [i.] follows from equations (1.5) and (1.6). Numeral [ii.] requires to check the first-order conditions (i.e. equations (1.3) and (1.4)) and it can be seen that $k \leq q_\Delta$ implies a corner solution.

Numeral [i.] of proposition 2 implies that entry occurs with positive probability (i.e $(1 - s_I^*)s_E^*$) when the cost of innovating, k, is relatively high. The intuition for this result is that for moderate costs of innovation, the incentives for the incumbent to innovate are high and therefore achieves the innovation with a high probability. Given that the entrant can only enter the market when the incumbent does not innovate, the entrant has lower incentives to innovate. As the cost of the innovation increases, the incumbent reduces his incentives to innovate and, hence, it is, in expectations, profitable for the entrant to keep investing. However, the installed base advantage of the incumbent limits the incentives to innovate for the entrant.

Numeral [ii.] of proposition 2 states that when the cost of innovation is too low no entry occurs. That is, the incumbent invests its maximum possible amount $s_I^* = 1$ and the entrant has no incentives to innovate and exhibit an investment level equal to $s_E^* = 0$.

These result of proposition 2 can be seen graphically. Figure 1.1 shows the equilibrium values s_I^* and s_E^*. For simplicity, this figure considers the case when $b = 1$ and $q_\Delta = 3$ but extends to any parameter configuration, such that the assumptions of the model hold.

Note in the graph the case when the cost of investment are zero or close to zero (i.e. no entry equilibrium due to $k \leq q_\Delta$). In that situation, the incentives to invest for

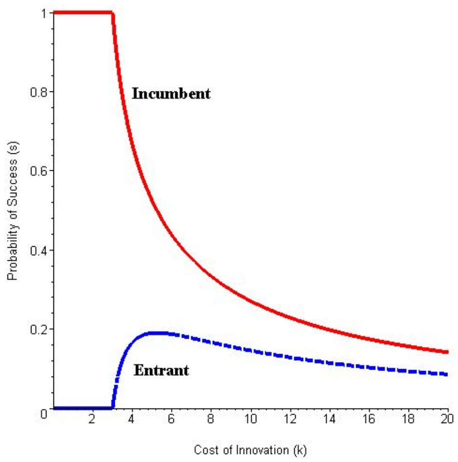

Figure 1.1: Market Outcome - Investment Levels

the incumbent are at its maximum ($s_I = 1$) because investing that amount implies the achievement of an innovation in the next period at a low cost, and therefore, securing its incumbent position. Conversely, the incentives to invest for the entrant are zero, even though investment is low or even costless. The reason is, no matter how much the entrant invests (even $s_E = 1$), the entrant is never going to takeover the market. Therefore, for costless investment the incumbent firm invests the maximum possible and the entrant firm performs no investment.

However, when the cost of investment starts increasing, it is extremely costly for the incumbent to carry out exactly the maximum possible investment. Therefore, it reduces slightly its level of investment, reducing at the same time its probability of success. As a consequence, now that the incumbent is not achieving the innovation with certainty, there is a room for the entrant to invest and, possibly, takeover the market. For low cost of investment and given that the entrant starts with no investment, the increasing possibility of overtaking the market, when the cost of investment increases, implies that the entrant also increases its investment level in order to take advantage of such opportunity. Nevertheless, as the cost of the innovation increases, the entrant cannot increase its investment level indefinitely because at some point investment efforts become too expensive. After that point, the investment level of the entrant firm must decrease on the cost of such investments. Note that it is always the case that

$s_I^* > s_E^*$.

This divergence in the investment levels of the two firms only arises because of the installed base that the incumbent built in period 1. Therefore, the extent of the network benefit is critical to this result and explains the asymmetric investment levels observed in equilibrium. This is stated in the following proposition.

Proposition 3 *Under assumption 1 assume that the network externalities increase (i.e. b increases). In equilibrium,*

i. The incumbent invests more in R&D.

ii. The entrant invests less in R&D.

Proof. Consider the derivative of equations (1.5) and (1.6) with respect to the network externalities parameter.

This proposition says that the presence of network externalities increases the incentives to innovate for the firm that exhibits the installed base. That is, the presence of locked-in consumers implies that successful improvements in the good offered can be profitable. On the other hand, the presences of installed bases reduces the incentives for the entrant firm due to the strategic substitutability with respect to the incumbent's investment level. This result is in contrast with those reported by Kristiansen (1996) in his proposition 2, where higher network benefits imply lower (higher) incumbent's (entrant's) incentives to innovate. One reason for this discrepancy, is due to the fact that the focus of his paper is on the riskiness associated to the R&D projects undertaken by the firms, and therefore, it implies a different modelling strategy as explained in the introduction.

The previous results can be seen in Figure 1.2. This figure shows that for $b = 0$ both firms exhibit the same incentives to innovate and the size of the difference depends on the extent of the network externalities. It can be shown that the level of R&D when $b = 0$ is symmetric and equal to $q_\Delta/(q_\Delta + k)$. As b increases, the incentives to innovate behave according to proposition 3.

In addition, the incentives to innovate are also affected by the size of the expected innovation. This result is presented in the following proposition.

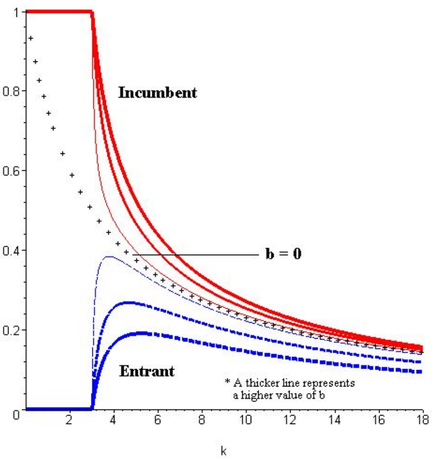

Figure 1.2: Investment Levels and Network Externalities

Proposition 4 *Assume that the value of the potential innovation increases (i.e. q_Δ increases). In equilibrium,*

i. The incumbent invests more in R&D.

ii. For low innovation costs the entrant invests less in R&D and the opposite occurs for moderate and high innovation costs.

Proof. Consider the derivative of equations (1.5) and (1.6) with respect to q_Δ.

Figure 1.3 shows that for moderate and high cost of the innovation, a higher size of the innovation tends to increase the incentives to innovate for both firms. This follows from the higher expected returns that can be made in the future if the installed base is increased (or captured) in period 2. This result is in line with the literature on the incentives to innovate, namely, a higher expected value of being the innovator increases the willingness to pay for the innovation.[6] In contrast, for low cost of innovation, a higher size of the innovation may reduce the incentives to innovate of the entrant firm. The intuition of this result is similar to the one presented for proposition 2. That is, when the cost of innovating is low, an increase in the size of the innovation increases the innovation incentives for the incumbent firm. This could lead the incumbent firm to carry out an investment level that is close to the maximum possible, hence, reducing

[6]See Reinganum (1989).

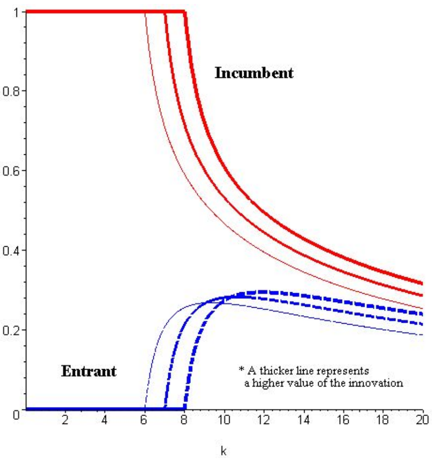

Figure 1.3: Investment Levels and Size of Innovation

the expected value of the innovation for the entrant and, in consequence, its innovation incentives.

One important question corresponds to the efficiency of the previous results. This analysis is taken into account in the next section.

1.4 Social Optimum

In order to analyze the efficiency of the market outcome presented above, this section analyzes the socially optimal outcome. We try to find out what are the differences in the privately determined investment behavior for the incumbent and the entrant firm and what is the role of network externalities in the potential inefficiencies. We first assume that in the second period adoption can be induced by a central planner. Thus, given the outcome of the innovation process, we are able to determine the network good that provide the higher surplus from a social perspective. Next, once we know which network good is going to be induced, we analyze the social incentives to undertake innovative initiatives. We consider the case where the following assumption holds.

Assumption 2 *The value of the innovation is greater than the value of the installed base of the old and new consumers.* $q_\Delta > 2b$.

This assumption is required to consider situations where it is socially optimal to introduce a new technology that is incompatible with the existing installed base.

1.4.1 Second Period Technology Adoption

We consider the maximum surplus that consumers can achieved in the second period given the four possible subgames (i.e. Γ^B, Γ^I, Γ^E and Γ^N). We take into account the surplus of the first consumer that is locked-in with the incumbent's good, and the surplus of the consumer that arrives in the second period.

In subgame Γ^B, the social surplus provided by the incumbent's good is equal to $q_1 + 2b$ and $q_2 + 2b$ for the first and second period consumer, respectively. This provides a total social surplus of $q_2 + q_1 + 4b$ in the second period if the network good of the incumbent firm is adopted. Analogously, the entrant's good provides a surplus equal to $q_1 + b$ and $q_2 + b$ for the first and second period consumer, respectively. The total social surplus from the entrant's good is $q_2 + q_1 + 2b$. Clearly, due to the role of the installed base, the incumbent's good provides a higher overall social surplus and therefore is adopted in the case subgame Γ^B is realized.

Following a similar analysis, we can show that in subgames Γ^I and Γ^N the incumbent's technology is induced with total surplus equal to $q_2 + q_1 + 4b$ and $2q_1 + 4b$, respectively.

Given assumption 2, in the case that subgame Γ^E is realized in the second period, it is socially optimal to induce the entrant's technology in the second period. Specifically, the entrant's good provides a total surplus of $q_2 + q_1 + 2b$.

Given the optimal choices of the central planner in the second period in terms of adoption, now we are able to calculate the socially optimal investment behavior. This is calculated in the next subsection.

1.4.2 First Period Investment Decisions

The central planner's objective function considered in the first period, given the optimal choice that is going to be observed in the second period once the innovation process is realized, is given by,

$$\begin{aligned}\max_{s_I,s_E} \quad & s_I s_E(q_2+q_1+4b)+s_I(1-s_E)(q_2+q_1+4b)\\ & +(1-s_I)s_E(q_2+q_1+2b)+(1-s_I)(1-s_E)(2q_1+4b)\\ & -ks_I^2/2-ks_E^2/2\end{aligned}$$

In order to express the results in a comparable way with respect to the analysis presented for the market outcome, it can be shown that adding and substracting q_1, the problem of the social planner can be written as,

$$\begin{aligned}\max_{s_I,s_E} \quad & s_I s_E(4b+q_\Delta)+s_I(1-s_E)(4b+q_\Delta)\\ & +(1-s_I)s_E(2b+q_\Delta)+4b(1-s_I)(1-s_E)\\ & +2q_1-ks_I^2/2-ks_E^2/2\end{aligned} \tag{1.7}$$

In consequence, the first-order conditions are given by,

$$q_\Delta - s_E(q_\Delta - 2b) - ks_I^{SO} = 0, \tag{1.8}$$

for the incumbent technology, and,

$$(1-s_I)(q_\Delta - 2b) - ks_E^{SO} = 0, \tag{1.9}$$

for the entrant technology.

As in the case for the market outcome, whenever the probabilities s_I and s_E are in the interval $(0,1)$, the second-order conditions are always less than zero. Therefore, we can find the social optimal levels by solving simultaneously equations (1.8) and (1.9) for the values of s_I^{SO} and s_E^{SO}. That is, the social optimal investment levels are given by,

$$s_I^{SO} = 1 - \frac{k(q_\Delta - k)}{(q_\Delta + k - 2b)(q_\Delta - k - 2b)} \tag{1.10}$$

$$s_E^{SO} = \frac{(q_\Delta - 2b)(q_\Delta - k)}{(q_\Delta + k - 2b)(q_\Delta - k - 2b)} \tag{1.11}$$

We can show the following results.

Proposition 5 *Without network externalities ($b = 0$) the social optimum and the market outcome are identical*

Proof. Comparing equations (1.5) and (1.6) for the market outcome and equations (1.10) and (1.11) for the social optimum, it can be seen that for $b = 0$ there is no inefficiency for any of the firms.

The result in proposition 5 permits us to isolate the impact of network externalities in the inefficiencies that may arise in the incentives to innovate for both firms.

In addition, by comparing the optimal levels of innovation with the levels achieved privately, we can state the following result.

Proposition 6 *In comparison with the social optimum,*

i. The incumbent exhibits a too low level of investment.

ii. The entrant exhibits a too high level of investment.

Proof. It follows from comparing equations (1.5) and (1.6) for the market outcome and equations (1.10) and (1.11) for the social optimum for cases where $b > 0$.

This result states that even though the incumbent has increased incentives to innovate given the presence of network externalities, those greater incentives are insufficient from a welfare perspective. The reason for this results comes from the fact that in the market outcome, the private incentives of the incumbent do not consider the potential loss that the first consumer can incur given that is locked-in. This result is presented in Figure 1.4.

For the case of the entrant, this result implies that, given that he can capture the market (i.e. make profits) only if he is the unique innovator, he would over-invest in

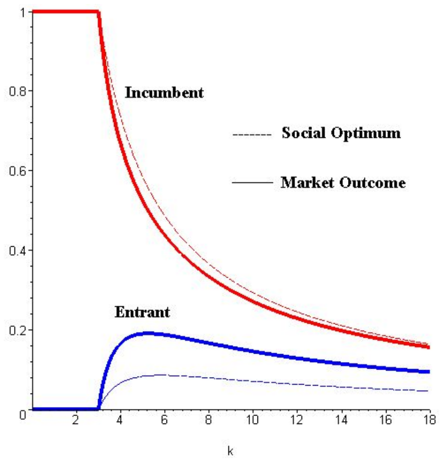

Figure 1.4: Social Optimum - Investment Levels

R&D. In this way, the entrant firm maximizes the probability of successful innovation in a socially inefficient way (i.e. rent dissipation). As stated in the introduction, Kristiansen (1996) presents the opposite result. That is, a potential entrant under-invests in R&D because he opts for a too certain R&D project, maximizing the probability of successful innovation. Therefore, even though the intuition in both cases is similar, the implications for R&D expenditures are the exact opposite and arise from the modelling strategy. We believe that in Kristiansen (1996), the assumed mean-preserving spread criterion, although it allows an analysis of R&D risk, it leads to a unrealistic prediction. In network industries entrants usually tend to heavily (over) invest in R&D in order to introduce new network incompatible technologies (e.g. interactive TV, Compact Disk (CD), Digital Versatile Disk (DVD), and digital imaging).[7]

The main implication of the results regarding the social efficiency of the market outcome is that, in equilibrium, the new incompatible technology (i.e. the entrant's network good) tend to be adopted too often. Kristiansen (1996) presents the same result. In his paper, entry occurs too often because the entrant chooses a too certain R&D project, implying a high rate of success and a too low level of investments. In the present model, entry occurs too often because the entrant invests too much in R&D

[7]Choi (1994) also presents a model where a potential entrant chooses a too certain R&D project in order to maximize the expected network size. However, Choi (1994) does not consider the implications for R&D expenditures that are the focus of the present chapter.

and captures the market too frequently. Therefore, even though his market outcome results differ from the ones presented here (i.e. he predicts an entrant's inefficient under-investment level), the consequences for social welfare are similar.

These results highlight the importance of an empirical analysis aimed at disentangle the true mechanism behind R&D incentives and the pattern of adoption of network goods. This is particularly relevant for the design of public policy. For instance, public policies that increase the incentives to innovate for entrant firms (i.e. tax exemptions, R&D subsidies, patents' design, etc.) will imply opposite effects for social welfare. In Kristiansen (1996), such policies will be welfare-enhancing because they will allow an entrant firm to choose a riskier project, invest more and reduce the inefficiently high entry rate. In the present setup, such policies will be welfare-reducing because they will increase the loss due to the rent dissipation in the R&D competition stage and will exacerbate the already too high rate of entry.

1.5 Compatibility

The last two sections dealt with the case when the two firms produce incompatible network goods. However, a common observation is the growing number of alliances in information-technology industries in order to attempt to determine common design features in emerging markets. Sometimes the alliances take the form of compatibility agreements (e.g. sharing technologies) in order to maximize network effects.

For instance, a consortium of electronics and computing companies working on DVD development are attempting to agree on common standards to try to avoid the VHS/Beta standards battle. IBM decided to open its PC architecture and Nokia announced that it would share its mobile technology with other firms.

At the same time, in some recent cases like the video game industry and the introduction of digital TV, it has been clear that competition takes place with incompatible standards. Moreover, there is no clear answer under which conditions industry competition favors compatibility or incompatibility. For instance, Phillips and Sony agreed on a Compact Disk (CD) standard but are now entering a contest to determine the new digital audio format.[8]

This section provides an illustration of the role of compatibility in a network market and its impact on the incentives to perform R&D investments. In the setup presented in this chapter, full compatibility implies that each group of consumers benefit from the total network effects. That is, additional to the stand-alone value of the network good, the value of the network benefits is common to all consumers and equal to $4b$. Therefore, in the price competition stage the network benefits provide no advantage to any firm and the first period R&D market equilibrium is identical to the case without network effects with optimal investments in R&D symmetric and equal to $q_\Delta/(q_\Delta + k)$ (i.e. a price-quality competition determined by a R&D race).[9]

However, what makes the present analysis different to a regular R&D race under quality differentiation is the impact on consumer surplus. That is, the network benefits do not affect the outcome of firms' competition and the social planner but do influence the final surplus enjoyed by consumers. By solving the problem under compatibility it can be shown that even though industry profits are always higher under incompatibility, a social planner would always impose a compatibility agreement.

Moreover, under compatibility, private R&D incentives are not only symmetric but efficient. This result is not surprising because compatibility implies that the network benefits are common to all groups of consumers, and this fact is known by private firms, as well as by the social planner.

However, note that this compatibility-led efficiency implies that the incumbent firm invests less and the entrant invests more than the levels that would be observed under incompatibility. Therefore, as the net effect depends on parameters' values, compatibility does not necessarily reduces the intensity of the R&D competition as has been suggested for example by Katz and Ordover (1990) and Kristiansen (1998). In consequence, it can be stated that compatibility *per se* does not reduce the pace of innovation in a network industry.[10]

[8]See Reilly (1993) and Besen and Farrell (1994).

[9]Under compatibility, the firms' problem is defined by $\max_{s_i} s_i(1-s_j)(q_\Delta) - ks_i^2/2$ where $i, j \in \{I, E\}$ and $i \neq j$. The social planner problem is equal to $\max_{s_I, s_E} s_I s_E(q_\Delta) + s_I(1-s_E)(q_\Delta) + (1-s_I)s_E(q_\Delta) + (1-s_I)(1-s_E) + 4b + 2q_1 - ks_I^2/2 - ks_E^2/2$.

[10]In the 70's, the US National Bureau of Standards refused to write interface standards for the

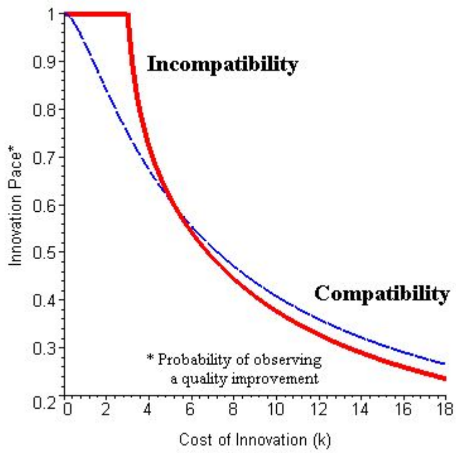

Figure 1.5: Innovation Pace

The reason for this, is the presence of endogenous and uncertain quality differentiation. In Kristiansen (1998) the only source of differentiation (in expectations) between the incumbent and the potential entrant is the presence of an installed base. Therefore, compatibility eliminates all possible source of advantages for the competing firms, while in our case differentiation can still be achieve through successful R&D initiatives.[11]

In our model, it can be shown that for high costs of innovation, compatibility actually increases the R&D competition intensity, evidencing a higher pace of innovation. Defining the pace of innovation as the probability of observing a quality improvement in any of the offered goods (i.e. $1-x$ where x is the probability that no firm innovates), Figure 1.5 shows this result.

1.6 Conclusions

In the present chapter, we have presented a simplified two-period duopoly model of competition with uncertain technological progress in order to determine the private incentives to innovate and its relation with the social incentives.

We have presented four main results. First, for low cost of innovation entry does not

computer industry claiming that standards would retard innovation. See Hemenway (1975).

[11]Farrell and Katz (1998) also argue that R&D competition with uncertain outcomes tends to create winners and losers. Winners prefer incompatibility.

occur at all and for high cost of innovating, entry occurs with positive probability. This result highlights the preemptive power of the innovation incentives. That is, for low cost of innovation the incumbent firm may increase enough the probability of achieving the innovation, eliminating the entrant's incentives to attempt to capture the market.

Second, when entry is possible, the incumbent invests always more that the entrant and, therefore, there is a high probability the the incumbent maintains its monopoly position. This result implies, that even though the incumbent has an advantage to keep monopolizing the market, he is forced to innovate given the threat of entry.

Third, from a welfare perspective, the incumbent invests too little and the entrant invests too much given the existence of locked-in consumers. That is, neither the incumbent firm nor the entrant takes into account the impact on welfare of the first period consumers and this generates the social suboptimal outcome. These efficiency results are solely due to the presence of network externalities.

Finally, fourth, by choosing to produce compatible products, firms do not necessarily reduce the R&D competition intensity as has been argued for example in Katz and Ordover (1990) and Kristiansen (1998). This is due to the presence of endogenous quality differentiation. Moreover, compatibility is always preferred from a social welfare perspective and for high cost of innovation it may even increase the pace of innovation observed in the industry.

It should be recognized that the model might, and should, be extended to a fully dynamic setting and must consider a richer set of options for the involved firms. In addition, comparison with case studies or empirical regularities might enrich the results.

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Chapter 2

Durable Goods, Innovation and Network Externalities

2.1 Introduction

An industry exhibits network externalities when the benefit that consumers enjoy from purchasing one or several of its goods depends on the number of other consumers that use the same and/or compatible products. For the firms in those sectors (e.g. software, telecommunications, consumer electronics, etc.), the presence of network externalities implies that the attractiveness of their products is a function of their quality-adjusted prices and the potential benefit attached to their expected network sizes (i.e. installed bases).[1]

Those products (i.e. network goods) tend to be characterized by two features closely related. Durability and rapid technological progress.[2] Durability implies that network goods tend to "wear out" not as a result of physical deterioration, but as a consequence of technical obsolescence; a feature due to technological progress. For example, a given software (or mobile phone, or video game, etc.) can be functional for a long time. However, the utility derived by its use tend to be dissipated due to new (and actually

[1] See Katz and Shapiro (1985, 1986) and Farrel and Saloner (1985, 1986) for seminal treatments, and Katz and Shapiro (1994) and Economides (1996) for surveys on network markets.

[2] See Katz and Shapiro (1999) for an informal analysis of antitrust in software markets, where these two characteristics are explicitly considered.

very frequent) developments that are more closely related to consumers needs and tastes.

This chapter considers a stylized network industry where these two feature, durability and technological progress, are analyzed together. In particular, we propose a model of R&D competition between an incumbent and a potential entrant and consider the implications of the durability of network goods. Our main objective, is to isolate the role of network externalities and analyze the social efficiency of the R&D incentives of the firms in this industry.

We depart from the current literature by considering, simultaneously, an oligopolistic setup, endogenous R&D processes and durable goods. Therefore, this chapter is not only closely related to the literature on durable goods and to the literature on technological progress in network industries, but represents a first step in bridge them together.

The economic literature has highlighted the role that durability plays in the evolution of a market dominated by a monopolist. In particular, the conventional problem for the monopolist is that, having sold a durable good, there is an incentive to reduce price later to bring into the market those consumers that would not pay the initial high price. However, consumers realize that the monopolist has such an incentive to reduce price once they have purchased and those that value the good less highly will withhold their purchase until price falls. For this reason the monopolist is unable to extract as much money from the market as would be possible with a pre-commitment of "no future price reductions". The fact that in the absence of commitment the monopolist may act against his own profitability implies a "time-inconsistency" problem (i.e. choices that maximize current profitability might not maximize overall profitability).

This notion was first discussed by Coase (1972) and has been labelled as the "Coase Conjecture".[3] Since its formulation, the Coase Conjecture has been theoretically developed in several papers that consider the robustness of the basic observation.[4]

[3] Strictly, the Coase Conjecture refers to a limiting case. It states that in the absence of commitment and if the monopolist may adjust its prices frequently enough, the successive price reductions lead to marginal cost pricing and the subsequent loss of market power.

[4] See, for example, Bagnoli, Salant and Swierzbinski (1989), Bulow (1982), Gul, Sonnenschein and Wilson (1986), and Stokey (1981).

The essential problem is that the monopolist's actions in the future provide competition for the company in the present market.[5] If the monopolist is able to lease the good, distort technology or implement buy back procedures then more profit can be extracted from the market since these strategies restrict the aftermarket.[6] Failing this the monopolist has an incentive to reduce durability or make the good obsolete after a period of time.[7] The existing analysis of durability in the presence of network externalities has intended, as the main literature on durability, to verify the validity of the Coase Conjecture.[8]

However, the implications of durability are much broader than the pricing commitment problem considered in the analysis of the Coase Conjecture. In particular, the result that a monopolist in the absence of commitment may affect its own overall profitability applies in several contexts. In fact, as pointed out by Waldman (2003), any present and future action that affects the future (relative) value of the monopolist's used goods might be subject to the "time-inconsistency" described above. One leading case of such actions is a firm's R&D expenditures which, by definition, affect the (relative) value of used (or previously sold) goods.[9]

In the presence of network externalities, the similar analysis of introduction of new durable goods has been analyzed.[10] However, this literature is focused on a monopolistic setup and considers the production of new technologies as exogenous. Hence, and to the best of our knowledge, there is no analysis that consider explicitly the process of endogenous R&D processes in the presence of network externalities and durable goods.

This chapter attempts to be a small step in that direction. As has been repeatedly highlighted in the literature, network goods are durable (e.g. consumer electronics, PCs, software) and their economic obsolescence follows from rapid technological progress instead of physical deterioration, implying the leading role of R&D incentives.

[5]The price of a durable good attempts to extract current and future surplus, however, future surplus depends on future actions that are not realized when the price is set.

[6]See Fudenberg and Tirole (1998), Kahn (1986) and Waldman (1997).

[7]See Bulow (1986), Hendel and Lizzeri (1999), Rust (1986) and Waldman (1993), Grout and Park (2005).

[8]See Bensaid and Lesne (1996), Cabral et al. (1999) and Mason (2000).

[9]See Waldman (1996), Fishman and Rob (2000) and Nahm (2004).

[10]See Choi (1994) and Ellison and Fudenberg (2000).

Moreover, even though network industries are characterized by a few number of successful incumbents (sometimes only one), entry does take place, making an oligopolistic analysis of R&D incentives with durable goods relevant.

The paper presented by Ellison and Fudenberg (2000) is the closest to this chapter and is actually our departure point. In that paper, the authors consider a monopoly that operates in a two-period framework and produces durable network goods. In the first period the monopoly produces a good with a given low quality and, subsequently, has the choice of introducing an improved version in the second period. Network externalities play a role because the improvement of the old good implies backward compatibility. That is, consumers of the new good enjoy network benefits from the entire population, while consumers of the old good only enjoy network benefits from consumers of the same good.[11]

In their model, there is an inflow of new consumers in the second period and, with consumer homogeneity, the paper shows that the monopolist has the incentive to introduce the improved good, even though the monopolist's overall profits (and social surplus) is reduced. That is, in the absence of commitment the monopolist's choice that maximizes current (second period) profits does not maximize overall profitability.

We present a model that extends that of Ellison and Fudenberg (2000) by introducing and endogenous R&D process in the production of the new technology, and consider the role of a potential entrant. We show results not present in the Ellison and Fudenberg (2000) analysis. In particular, we consider a two-period framework with an incumbent, a potential entrant and an inflow of new consumers. Consumers are homogeneous and participate in a market with durable network goods.

In the first period, there is a first group of consumers that buy a network good from the established incumbent. Before the second period starts, a potential entrant appears in the market and, jointly with the incumbent, decides on an investment level that will allow him to compete in the second period. This R&D process is stochastic. By investing a certain amount, both firm determine the probability that in the second

[11]A case of this situation was evidenced by the launch of Microsoft Word 97. Consumers of Word97 were fully compatible with consumers of Word95 but the opposite did not hold.

period they are able to produce a new product that is quality-improved relative to the existing good produced by the incumbent. Conditional on the success or failure of the innovation process, both firms compete in price in the second period when a new group of consumers arrive.

We analyze the incentives to innovate for both firms, we compare it to the social optimum and investigate the role of the network externalities. With our simplified approach, we are able to isolate the impact of network externalities and reach three main results.

First, the threat of entry reverses the commitment problem that a monopolist (without such threat) may face in its R&D decision given good durability. This result is not present in the current literature and follows from the role that R&D incentives play in deterring entry. In our case, the monopolist's commitment problem arises only due to the presence of network externalities.

Second, the levels of R&D determined by market outcome might differ from the socially optimal levels. In particular, a potential entrant always over-invests (as an entry strategy) and an established incumbent might exhibit higher, lower or equal R&D levels in comparison with the social optimum. This result suggests that successful entry takes place too often in comparison with the social optimum.

And third, the extent of network externalities is the crucial parameter in the efficiency of the incumbent R&D level. In fact, it is only the presence of network externalities that permits, potentially, to the established incumbent to provide an efficient level of innovation. Without network externalities (or very low network effects), it is shown that the incumbent firm always under-invests in R&D efforts. This result sheds some light on the debate whether a dominant incumbent in a network industry provides sufficient innovation to the society.

The chapter is organized as follows. The next section presents the model. Section 3 presents the analysis of its equilibrium. Section 4 computes the social optimum and compares it with the results of the market outcome. Finally, section 5 concludes and discusses some areas of further research.

2.2 The Model

We consider a model of a network industry with durable goods based on that of Ellison and Fudenberg (2000).[12] There are two periods denoted by $t = 1$ and $t = 2$ with a group of homogeneous consumers arriving in each period. In period 1 there is a monopolist incumbent that is challenged in period 2 by a potential entrant. In period 2, firms compete in prices with quality differentiated products. Quality is determined through endogenous and stochastic R&D processes carried out in period 1.

2.2.1 Supply Side and R&D Process

In period 1, an incumbent monopolist, I, produces a durable network good with quality level q_1 (i.e. stand-alone value). The good lasts two periods after which it vanishes. We consider the case of product innovations where, subject to R&D expenditures, the incumbent might be able to produce a network good of better quality to be introduced in period 2. In our model, this process of innovation is carried out at the end of period 1. In addition, we assume that the outcome of the R&D process is stochastic with two possible outcomes, success or failure. This outcome is realized at the beginning of period 2.

In particular, we consider an R&D process where the incumbent firm determines the probability s_I that the innovation process is successful. Higher investments (i.e. higher probability of success) entail higher costs. These costs are summarized by means of a function $C(s_I)$ that is increasing in the probability of success s_I. For simplicity, we assume that $C(s_I) = \frac{as_I^2}{2}$, where a is a cost parameter.

In the case of success, the innovation is achieved and allows the incumbent firm to produce a "new" network good with quality q_2 in period 2, where $q_2 = q_1 + q_\Delta$ and q_Δ is the extent of the innovation. q_Δ is assumed to be constant and greater than zero. If the innovation process is unsuccessful, the incumbent produces in period 2 the same "old" good with low quality q_1. It is assumed that the achievement of the innovation

[12]We construct our model to make Ellison and Fudenberg (2000) a particular case of the one presented here.

do not preclude the incumbent to produce the "old" good in period 2.

In addition, we introduce a potential entrant, E, that intends to compete with the incumbent in period 2. In order to be able to enter the market, the potential entrant must invest in R&D to develop a network good. The entrant's innovation process takes place simultaneously with that of the incumbent firm. It is assumed, that the innovation process for the potential entrant is identical to the one of the incumbent firm. Therefore, the potential entrant must determine the probability s_E, that its innovation process succeeds. If so, the entrant is able to produce the "new" good with quality q_2 in period 2. It is assumed that in the case of unsuccessful innovation, the entrant firm stays out of the market (i.e. it cannot produce the old quality network good).

As in Ellison and Fudenberg (2000), we assume that the network goods are backward compatible. That is, consumers of the new good enjoy network benefits from all users (i.e. users of new and old goods), while consumers of the old good only enjoy network benefits from consumers of the same good (e.g. Word97 vs. Word95).[13]

It is further assumed that the firms cannot change the quality of the goods once they are already produced. Marginal costs of production are independent of quality and set equal to zero. For simplicity the discount factor is equal among firms and normalized to 1.

2.2.2 Demand Side and Expectation Formation Process

The demand side represents the core of the model. In each period there is a group of N_t homogeneous consumers arriving in the market and, for convenience, we normalize $N_1 + N_2 = 1$. Consumers exhibit a per-period unitary demand for a network good and buy as soon as they reach the market. This implies that the N_1 consumers make a purchase decisions in period 1 and in period 2. Given durability, this is not a trivial implication.

[13]Note that the assumption of backward compatibility implies that, conditional on successful innovation, the surplus offered by the new good is independent of the identity of the firm that produces it.

To see this, note that the price charged to the N_1 consumers in period 1 tries to extract period 1 and 2 surpluses (i.e. the good is durable). However, period 2 surplus is affected by the outcome of the R&D processes, the prices of the two firms in period 2 and the N_1 and N_2 consumers' choices. Therefore, the willingness to pay of the N_1 consumers in period 1 depends on their beliefs on how the firms are going to behave in period 2. This gives rise to the commitment problem discussed in the introduction.

Consider first period 1. The first group of consumers, with size N_1, arrives at the beginning of period 1, finds only the incumbent's good and observes its price (to be derived below). We model utility by assuming that each consumer in N_1 derives a first-period benefit (gross of price) from buying from the incumbent firm given by $q_1 + \alpha x - c$. In this expression, q_1 is the quality of the good, α is a parameter that measures the extent of the network benefits, x is the number of users of compatible goods[14] and c is a cost of learning to use the network good. We introduce the following assumptions.

Assumption 3 $2q_1 > 0$. *N_1 always consume the old good in period 1.*

By introducing assumption 3, the model implies that even in the case where network benefits are equal to zero, first period consumers always consume. This assumption will allow us to analyze the model with very small (or non-existent) network benefits and compare the results with the case where network externalities are important without introducing discontinuities in the consumers' behavior.

Assumption 4 $q_1 + \alpha N_1 - c_u > 0$. *It is optimal for N_1 to consume in both periods.*

The previous assumption 4 is introduced to avoid the possibility of N_1 consumers waiting to period 2 to consume.[15] This assumption reduces the number of cases to be analyzed, and allows us to focus on the results we are interested in.[16]

[14] Note that given the homogeneity of the consumers $x = N_1$ in period 1.

[15] In order to maintain the order of the exposition, the parameter c_u (i.e. the cost of upgrading) is introduced below.

[16] See, for example, Choi and Thum (1998) for the analysis when consumers can wait to adopt a network good.

Of course, the overall benefit enjoyed by consumers in N_1 also depends on period 2 choices to be explained below. Note that at the beginning of period 2, the outcome of the innovation process is realized depending on the investment decisions. Hence, there are four possible cases in period 2; no firm innovates; only the incumbent or only the entrant innovates; and both firms achieve the innovation.

Now consider period 2. When the N_1 consumers reach the beginning of period 2, they observe the outcome of the innovation process. If the innovation is achieved, the N_1 consumers evaluate the incremental utility from purchasing (i.e. upgrading to) the new generation of the good and decide accordingly.[17] Therefore, they compare the benefit (gross of price) from the new good $q_2 + \alpha(N_2 + x) - c_u$ with the second-period benefit of staying with the old good $q_1 + \alpha x$. c_u is the cost of learning to use the new generation (i.e. cost of upgrading). It is assumed that $c_u < c$. As common in models with network externalities, the equilibrium value of x depends on the way consumers form expectations about other consumers behavior.

We assume that consumers are able to coordinate on the outcome that maximize their surplus (i.e. Pareto-Optimal coordination equilibrium).[18] In other words, consumers are able to coordinate on the choice that maximize joint surplus. Thus, they compare $q_2 + \alpha - c_u$ with $q_1 + \alpha N_1$ and, in consequence, the incremental utility from upgrading is given by $q_\Delta + \alpha N_2 - c_u$. Hence, whenever $q_\Delta + \alpha N_2 - cu > 0$ upgrade by the N_1 consumers takes place, otherwise the N_1 consumers do not buy the new good and stay with the old one. We denote this (candidate) price of upgrading as p_u.

In period 2, a second group of consumers with size N_2 arrives in the market. This group of consumers observes the outcome of the innovation process, observes prices (to be derived below) and makes purchase decisions. In particular, it is assumed that whenever the innovation is successful (either by the incumbent, the entrant or both) the N_2 consumers do not exhibit any preference for the old good produced by the incumbent. That is, the willingness to pay of N_2 consumers for the new generation of

[17] Recall that for the N_1 consumers the identity of the firms that produces the new good in period 2 is irrelevant (footnote 14).

[18] See Katz and Shapiro (1986) and Farrell and Katz (2005).

the good is equal to $q_2 + \alpha - c$.[19] We denote this (candidate) price as p_n. Note that given the assumption of backward compatibility, consumers of the new good enjoy the full network benefits (i.e αx with $x = 1$).

In the case that the innovation does not take place (i.e. no firm innovates), the N_2 consumers decides for the old good with a willingness to pay equal to $q_1 + \alpha - c$. We denote this (candidate) price as p_o. Therefore, analogous to Ellison and Fudenberg (2000), it is the choice of the N_1 consumers in period 2 that represents the most important part of the analysis.

In the next section we present the main results of the market outcome.

2.3 Market Outcome

In this section we consider the optimal pricing decision and the private incentives to innovate of the two firms. As a benchmark, we consider first the monopoly case. This analysis will allow us to compare the present chapter with the current literature, to analyze the impact of network externalities and highlight the main results we obtain in comparison with Ellison and Fudenberg (2000). Once the monopoly case is considered, we analyze the model where the incumbent monopolist faces the threat of entry. In both cases, we consider the commitment as well as the no commitment case given its role in the durability literature discussed in the introduction.

As has been widely highlighted in the literature, the no commitment case is equivalent to focus on the Subgame-Perfect Nash-Equilibrium (SPNE), and the commitment case corresponds to the Nash-Equilibrium (NE) of the global multi-stage game.

2.3.1 A Monopoly Model

In order to solve the monopoly model, we first solve for the period 2 demands, profits and price equilibria. Then, we turn to the investment decision at the end of period 1 and derive the commitment and the no commitment case.

[19]This assumption allows the incumbent monopolist to extract the full consumers surplus in the case without entry. Therefore, it permits us to conclude that any reduction in the monopolist's profit implies a reduction in social welfare.

Second Period - Pricing Decision

Before deriving the equilibrium prices conditional on the outcome of the R&D process, it is important to note that the value of p_u is critical to the analysis because it describes the situation where upgrade takes place.

Assumption 5 $p_u > 0$. *Whenever the new good is produced, it is optimal for* N_1 *to upgrade.*

We focus on the analysis, unless otherwise noticed, for cases when assumption 5 holds. (i.e. upgrade is possible and optimal) and later on we present a brief discussion considering the case when assumption 5 does not hold.

Note that price competition depends on the outcome of the innovation process, therefore, there are two cases to consider according to the success or failure of the monopolist's innovation process.

Monopolist does not innovate. In this case, the monopolist still produces the old good with quality q_1 in period 2. As explained before, the N_1 consumers do not make any purchase decision (they already have the only existing good) and the N_2 consumers buy the old good if the price is less or equal to the maximum surplus offered by the good (i.e. $p \leq p_o$). Therefore, given the homogeneity of consumers, the incumbent charges p_o to the N_2 consumers that are his only revenue source and extract their full surplus.

Monopolist does innovate. In this case, the new generation of the good with quality q_2 is produced by the monopolist. Under assumption 5 and the coordination assumption, it is optimal for the N_1 consumers to upgrade if the price charged is less or equal to the incremental surplus offered by the new good (i.e. $p \leq p_u$). Again, given consumer homogeneity, the monopolist charges p_u to the N_1 consumers. Using similar arguments, it can be shown that the monopolists charges p_n to the N_2 consumers. Note that innovation increase the source of revenues for the incumbent.

Table (2.1) summarizes the pricing decision by the monopolist in period 2 conditional on the outcome of the R&D process. Each cell in the table shows the price charged to the N_1 and the N_2 consumers, respectively.

	Monopoly does not innovate	**Monopoly does innovate**
Monopolist's Prices	0 $q_1 + \alpha - c$	$q_\Delta + \alpha N_2 - c_u$ $q_2 + \alpha - c$

Table 2.1: Period 2 - Pricing Decision - Monopoly case

First Period - Investment Decision

Suppose that to obtain the improved quality in period 2, the monopoly has to invest and succeed according to the R&D process described above. That is, the monopolist must decide the probability s that in period 2 the innovation is achieved and the new generation of the good with quality q_2 is produced.[20] The cost of choosing the probability s is given by $C(s) = \frac{as^2}{2}$, where a represents a cost parameter. Assume that consumers coordinate on the Pareto-optimal equilibrium. Then, if the innovation is successful, for $q_\Delta + \alpha N_2 - c_u > 0$ (i.e. assumption 5 holds) in period 2 the N_1 consumers upgrade and pays a price p_u and the N_2 consumers adopt the new good. If $q_\Delta + \alpha N_2 - c_u < 0$ (i.e. given that the innovation is achieved and assumption 5 does not hold) the N_1 consumers do not upgrade and the N_2 consumers adopt the new technology. If the innovation is not achieved, the N_1 consumers do not make any decision and the N_2 consumers adopt the old good. Consider the case where assumption 5 holds, then, the investment problem of the monopolist and the end of period 1 is given by,

$$\max_s \Pi_M = N_1 p_1 + s(N_1 p_u + N_2 p_n) + (1-s)(N_2 p_o) - \frac{s^2}{2} \tag{2.1}$$

with,

$$p_1 = q_1 + \alpha N_1 - c + s(s_n - p_u) + (1-s)(s_o)$$

In this expressions, we have simplified considering $a = 1$ $p_u = q_2 - q_1 + \alpha N_2 - c_u$, $p_n = q_2 + \alpha - c$, $p_o = q_1 + \alpha - c$, $s_n = q_2 + \alpha - c_u$ and $s_o = q_1 + \alpha$.

In this expression, $N_1 p_1$ corresponds to the period 1 revenues, $s(N_1 p_u + N_2 p_n) +$

[20] Note that if the innovation can be achieved with certainty and at no cost, the analysis is the one presented in Ellison and Fudenberg (2000)

$(1-s)(N_2p_o)$ are the period 2 revenues and $\frac{s^2}{2}$ is the cost attached to the innovation process.

Consider the revenues obtained in period 1. As can be seen, p_1 extracts the full surplus enjoyed by the N_1. In particular, $q_1+\alpha N_1-c$ represents the period 1 surplus and $s(s_n-p_u)+(1-s)(s_o)$ is the expected period 2 surplus that is conditional on the outcome of the innovation. That is, with probability s the innovation is achieved and, given assumption 5 holds, it is optimal for the N_1 consumers to upgrade in period 2 with a net surplus of s_n-p_u. On the other hand, if the innovation is not achieved, the period 2 net surplus of the N_1 consumers is equal to s_o.

Importantly, note that the price charged in period 1, p_1, depends on the level of investment because the surplus that the N_1 consumers enjoy in period 2 is uncertain at the beginning of period 1. Moreover, observe that $\frac{\partial p_1}{\partial s}=-\alpha N_2<0$. This observation implies that through investment, the monopolist reduces the future value of its good sold in period 1. Therefore, a higher R&D investment reduces the willingness to pay from the N_1 consumers in period 1 as the durability literature suggests. At the same time, a higher investment level increases the probability of introducing a new generation of the network good in period 2, and in consequence, expected period 2 revenues are increased. As we will see, it is the interaction (i.e. trade-off) between these two effects that represents the main impact of durability in the R&D incentives by the monopolist and highlights the role of commitment.

The revenues obtained in period 2 presented by the second and third term of equation (2.1) have an straightforward interpretation. In the following, we solve for the optimal investment decision given the problem stated in equation (2.1). We first present the no commitment case and then the commitment case.

No Commitment Case

Under no commitment the analysis of the SPNE rule out any non-credible threats by the monopolist. Therefore, consumers in period 1 determine their willingness to pay considering the case of what would the monopolist do after the N_1 consumers have made their period 1 purchasing decision. In other words, solving backwards and considering the R&D level that maximizes second period profits for the monopolist, we obtain the following first-order condition,

$$0 = N_1 p_u + N_2 p_n - N_2 p_o - s^{nc}$$

It can be seen that the second-order condition for an interior solution also holds. Thus, the corresponding optimal level of investment in the absence of commitment by the monopolist is given by,

$$s^{nc} = q_\Delta - N_1 c_u + \alpha N_1 N_2 \tag{2.2}$$

Before analyzing this result, we solve first for the commitment case.

Commitment Case

In this case, the monopolist is able to internalize the negative impact that his investment decision has on the first period prices (i.e. recall $\frac{\partial p_1}{\partial s} < 0$). Therefore, by considering the NE of the global multi-stage game, we obtain the following first order condition,

$$0 = -N_1 N_2 \alpha + N_1 p_u + N_2 p_n - N_2 p_o - s^c$$

Analogously, the second-order condition for an interior solution holds and the optimal level of investment provided that the incumbent is able to commit is given by,

$$s^c = q_\Delta - N_1 c_u \tag{2.3}$$

As can be readily seen from the preceding analysis, $s^{nc} > s^c$ holds for any parameter configurations. This results is not surprising and is in line with the traditional literature. It says that without commitment, the monopolist has the incentive to invest more than in the presence of commitment because it does not internalize the negative impact of its investment level on the price charged in period 1. Moreover, it is evident that the difference between the two investment levels is equal to $\alpha N_1 N_2$ which vanishes when the network externalities are not present (i.e. $\alpha = 0$). This implies that the effect of commitment is completely isolated and will allow us to conclude that any inefficiency, if present, will be solely due to the presence of network externalities.[21]

This result is stated in the following proposition.

Proposition 7 *Without the threat of entry, the monopolist invests more in the absence of commitment than it would be the case if commitment is possible. This difference is only due to the presence of network externalities.*

In addition, comparing the two profit levels (solving for the corresponding optimal investment levels in equation (2.1)) it can be shown that $\Pi_M^c - \Pi_M^{nc} = \frac{(N_1)^2(N_2)^2\alpha^2}{2}$ which is unambiguously positive. Again, this result highlights the main commitment problem on the R&D incentives of a monopolist that arises in the presence of durable goods (see Waldman (1996)). That is, once a monopolist does not have the possibility to commit to future R&D investments, its optimal decision affects negatively its overall profitability. Importantly, note that the previous result vanishes if $\alpha = 0$.

In addition, given that consumers are homogeneous, the monopolist is able to extract all the surplus from the consumers and, therefore, the absence of commitment reduces social surplus.

Proposition 8 *For the monopoly case, the absence of commitment in the R&D investment implies a lower social surplus compared to the case when commitment is possible. This result is only due to the presence of network externalities*

The analysis of the monopoly model presented two main results. First, the presence of network externalities implies a commitment problem in the investment decision by the monopolists. This commitment problem is represented by an over-investment in comparison with the case where commitment is possible. And second, due to the presence of network externalities, the commitment problem implies a lower overall profit and an associated lower social welfare. These results are in line with the current literature and represent the benchmark for comparison for our analysis of entry.

[21]This result also holds in the Ellison and Fudenberg (2000) paper.

2.3.2 A Model with Entry

In this subsection we extend the monopoly analysis presented above and consider the case of a potential entrant. Keeping the same framework, we model the case of an incumbent monopolist that serves the entire market in period 1 and must compete with a potential entrant in period 2. As explained before, entry is conditional on innovation and, therefore, both firms invest in developing a new technology at the end of period 1. At the beginning of period 2 the outcome of the innovation process is realized and price competition takes place.

As in the analysis of the monopoly case, the investment decision depends on the equilibrium concept adopted, namely, SPNE or NE, which characterizes the no commitment and commitment case, respectively. In order to proceed, we first solve for the period 2 demands, profits and price equilibria that follow from Bertrand competition. Then, we turn to the strategic investment decision at the end of period 1 and derive the commitment and the no commitment case.

Second Period - Price Competition

As in the monopoly analysis and in order to simplify exposition, we assume in what follows that assumption 5 holds. Note that price competition depends on the outcome of the innovation process, therefore, there are four cases to consider according to the success or failure of a given firm's innovation process, and the identity of that firm.

No firm innovates. In this case, no firm achieves the innovation. In consequence, the incumbent firm still produces the old good with quality q_1 in period 2 and the entrant firm has no production. As explained before, the N_1 consumers do not make any purchase decision (they already have the only existing good) and the N_2 consumers buy the old good if the price is less or equal to the total surplus they get from it. Therefore, the incumbent is able to charge p_o to the N_2 consumers that are his only revenue source in period 2. Note that this case, ex-post, is identical to the monopoly case without innovation.

Only Incumbent innovates. In this case, the new generation of the good is

Firm	**Both Firms Innovate**	**Incumbent Innovates**	**Entrant Innovates**	**No Firm Innovates**
Incumbent's Prices	0 0	$q_\Delta + \alpha N_2 - c_u$ $q_2 + \alpha - c$	0 0	0 $q_1 + \alpha - c$
Entrants's Prices	0 0	0 0	$q_\Delta + \alpha N_2 - c_u$ $q_2 + \alpha - c$	0 0

Table 2.2: Period 2 - Price Competition - Entry case

produced by the incumbent and the entrant does not enter the market. Therefore, given the assumption that the consumers are able to coordinate on the Pareto-Optimal equilibrium, the incumbent charges p_u to the N_1 consumers and p_n to the N_2 consumers. Note that innovation increase the source of revenues for the incumbent. Given that entry does not take place, this case is, ex-post, identical to the monopoly case with successful innovation.

Only entrant innovates. In this case, the entrant innovates and is able to produce the new generation of the good in period 2. Therefore, the entrant firm is able to capture the N_2 consumers and charges p_n to them. In addition, and assuming that he can identify the N_1 consumers (i.e. the entrant can offer a cross-subsidy), the price charged to them is p_u subject to the coordination assumption discussed above.[22]

Both firms innovate. In this case, both firms achieve the innovation and compete with homogeneous products in a homogeneous market. Thus, Bertrand competition drives prices and period 2 profits to zero.

Table (2.2) summarizes the pricing decision in period 2 conditional on the outcome of the R&D process. Each cell in the table shows the price charged to the N_1 and the N_2 consumers, respectively.

First Period - Investment Decisions

After deriving the equilibrium prices from the competition in period 2 between the incumbent and the potential entrant, we are able to analyze the optimal investment decisions by the two firms. Note that in the case of the threat of entry, the investment

[22]Note that if the entrant cannot offer a cross-subsidy, the price charged to the N_1 is in any case equal to the incremental benefit that those consumer enjoy by purchasing the new good from the entrant firm.

decisions are derived strategically.

As explained before, the investment decisions correspond for the firms to choose the probability, s_k for $k \in I, E$, that the innovation is achieved in period 2. In addition, there is a cost $C(s_k) = \frac{as_k^2}{2}$ associated with a given probability s, where a correspond to a cost parameter.

The overall problem of the incumbent firm is given by,

$$\max_{s_I} \Pi_I = N_1 p_1 + s_I(1 - s_E)(N_1 p_u + N_2 p_n) + (1 - s_I)(1 - s_E)(N_2 p_o) - \frac{s_I^2}{2} \tag{2.4}$$

with,

$$p_1 = q_1 + \alpha N_1 - c + s_I(1 - s_E)(s_n - p_u) + (1 - s_I)(1 - s_E)(s_o)$$

In this expressions, we have simplified considering $a = 1$ $p_u = q_2 - q_1 + \alpha N_2 - c_u$, $p_n = q_2 + \alpha - c$, $p_o = q_1 + \alpha - c$, $s_n = q_2 + \alpha - c_u$ and $s_o = q_1 + \alpha$.

In this expression, $N_1 p_1$ corresponds to the period 1 revenues, $s_I(1 - s_E)(N_1 p_u + N_2 p_n)$ are the period 2 revenues that can be obtained if the incumbent firm is the only innovator, $(1 - s_I)(1 - s_E)(N_2 p_o)$ are the period 2 revenues for the case where no firm innovates, and $\frac{s_I^2}{2}$ is the cost attached to the innovation process. Recall that if the two firms innovate, profits are dissipated due to the price competition and that there is no revenues for the incumbent if the potential entrant is the unique innovator.

Consider the revenues obtained in period 1. As can be seen, p_1 extracts the full surplus enjoyed by the N_1 by charging the total surplus enjoyed in period 1 (i.e. $q_1 + \alpha N_1 - c$) and the expected surplus enjoyed in period 2 (i.e. $s_I(1 - s_E)(s_n - p_u) + (1 - s_I)(1 - s_E)(s_o)$). Moreover, as in the monopoly case, the period 1 price charged by the incumbent decreases with its own investment level. In particular, $\frac{\partial p_1}{\partial s_I} = -\alpha N_2(1 - s_E) < 0$. This observation implies that through a higher level of investment, the incumbent firm reduces the willingness to pay of the N_1 consumers in period 1. At the same time, and similar to the monopoly case, higher investments boost period 2 revenues. However, investments in the context analyzed in this subsection play an additional role: deter entry. Therefore, we analyze not only the trade-off between more revenues in period 1 or 2, but also consider the preemptive role of investments.

Analogously, the problem of the entrant firm is given by,

$$\max_{s_E} \Pi_E = s_E(1 - s_I)(N_1 p_u + N_2 p_n) - \frac{s_E^2}{2} \tag{2.5}$$

Again, we have simplified using $a = 1$ $p_u = q_2 - q_1 + \alpha N_2 - c_u$, $p_n = q_2 + \alpha - c$, $p_o = q_1 + \alpha - c$, $s_n = q_2 + \alpha - c_u$ and $s_o = q_1 + \alpha$. Note that the entrant can only have positive revenues if it is the unique innovator. In addition, it is important to highlight that the fact that the potential entrant has no period 1 revenues, it will not face any commitment problem. However, given that the investment levels are obtained strategically, the behavior of the incumbent has an important impact on the behavior of the potential entrant.

No Commitment Case

As in the monopolist problem, this case is obtained by focusing on the SPNE. Accordingly, the first-order condition for the incumbent firm taking into account only second period profits is given by,

$$0 = (1 - s_E)(N_1 p_u + N_2 p_n) - (1 - s_E)(N_2 p_o) - s_I^{nc} \tag{2.6}$$

Considering equation (2.5), the SPNE concept provides the first-order condition for the entrant firm given by,

$$0 = (1 - s_I)(N_1 p_u + N_2 p_n) - s_E^{nc} \tag{2.7}$$

It can be seen that the second-order conditions for an interior solution are satisfied. Thus, solving equations (2.6) and (2.7) provides the equilibrium R&D levels for the incumbent and the entrant firm in the absence of commitment by the incumbent firm. Again, note that given that the entrant firm only competes in period 2, it has no choice concerning a committed action. Before analyzing the results, we calculate first the commitment case.

Commitment Case

As should be clear by now, the NE of the global game represents the commitment solution and provides the following first-order condition for the investment level by the incumbent. That is,

$$\begin{aligned} 0 = {} & N_1((1-s_E)(s_n-p_u)-(1-s_E)(s_o)) \\ & +(1-s_E)(N_1p_u+N_2p_n)-(1-s_E)(N_2p_o)-s_I^c \end{aligned} \tag{2.8}$$

Analogously, the first-order condition for the entrant firm is,

$$0 = (1-s_I)(N_1p_u+N_2p_n)-s_E^c \tag{2.9}$$

As in the case of no commitment, solving equations (2.8) and (2.9) provides the equilibrium investment levels for both firm in the presence of commitment of the incumbent firm. In order to simplify the analysis (given the large number of parameters), we consider the behavior of the best response functions described by the first order conditions. Given the specifications on the R&D processes, from observations of equations (2.6) and (2.7) for the no commitment case, and equations (2.8) and (2.9) for the commitment case, the best response functions are linear and therefore provide a unique equilibrium. Moreover, they are downward sloping implying strategic substitutability in the investment levels. We require and additional assumption to guarantee the existence of an economically plausible equilibrium.

Assumption 6 $q_2 < 1+c_u-\alpha$. *The best response functions that describe the incentives to innovate are stable.*

As can be seen, assumption 6 restricts the size of the innovation. This assumption guarantees, in addition to provide stability to the best response functions, that for any parameter configurations, the probabilities of success lie on the interval $(0,1)$. Figure

2.1 shows the behavior of the best response functions and suffices to provide the main results.

As can be seen from the figure, $R_E(s_I)$ represents the best respond function for the entrant as a function of the investment level of the incumbent firm. This function is obtained from solving equation (2.7) for s_E^{nc}.[23] Equivalently, the best respond functions for the incumbent firm, $R_{Inc}(s_E)$ and $R_{Ic}(s_E)$, are obtained from solving equations (2.6) and (2.8) for s_I^{nc} and s_I^c, respectively. It can be shown that under assumption 6 the best response functions lie always on the positive quadrant and below 1.

In particular, the analysis of the market outcome is summarized in Figure 2.1. Figure 1a shows the case where network externalities are important and Figure 1b shows the case without network externalities. Figure 1a shows two main results. First, independent of the presence of commitment, the potential entrant always invest more that the incumbent firm. That is, in any case the equilibrium lies below the 45 degree line. And Second, as explained above, in the absence of commitment, the incumbent firm does not internalize the negative effect that its own investment has on his first period price and, therefore, invest more than it would be the case if commitment is possible. As a consequence, once commitment is considered the incumbent corrects its R&D expenditures negatively. This correction implies a stronger incentive for the entrant to innovate and, hence, increases the entrant's level of investment. In Figure 2.1 this is represented through the fact that the commitment equilibrium lies below and to the right of the no commitment equilibrium. This result holds for any parameter configuration satisfying the assumptions of the model.

Proposition 9 *Independent of the possibility of commitment by the incumbent, the potential entrant always invests in R&D more than the incumbent firm. Moreover, this difference is increased if commitment is possible.*

In addition, from equations (2.6) and (2.8) it can be shown that the difference between the commitment and no commitment case is only due to the presence of

[23] Note that the form of $R_E(s_I)$ does not depend on the presence of commitment because the entrant only competes in period 2. Therefore, $R_E(s_I)$ can also be obtained from solving equation (2.9) for s_E^c.

network externalities. This is represented in Figure 2.1 by the fact that the difference between the best response function of the incumbent without commitment lies above the best response function in the presence of commitment. In particular, the difference between the points at which both lines intersect the vertical axis is always positive and equal to $\alpha N_1 N_2$. Therefore, the strategic impact of entry is completely isolated. Figure (1b) shows a particular case with $\alpha = 0$.

Proposition 10 *The difference in the optimal investment levels with or without commitment is only due to the presence of network externalities.*

Importantly, several numerical analyses suggest that, for some parameter configurations, the profit of the incumbent is higher in the absence of commitment than it would be the case if commitment is possible. That is, the threat of entry implies that in some special cases it is strategically optimal for the incumbent to increase its R&D investment as a mechanism to response to the potential entrant. This result is in clear contrast with the monopoly analysis presented before and, therefore, extends the analysis of Ellison and Fudenberg (2000).

The result that the threat of entry may eliminate the commitment problem of a monopolist in durable goods market has been analyzed by Bucovetsky and Chilton (1986), Ausubel and Deckenere (1986) and Vettas (2001). However, to the best of our knowledge, there is no analysis that considers the role of R&D incentives in this situation and, therefore, our result differs from the current literature.

Proposition 11 *With the threat of entry, the incumbent firm may achieve a higher profit by strategically not committing its investment level. This is in contrast to the case without the threat of entry.*

One of the main objectives of this chapter is to analyze the social efficiency of the incentives to innovate in the presence of network externalities and durable goods. This is the purpose of the next section.

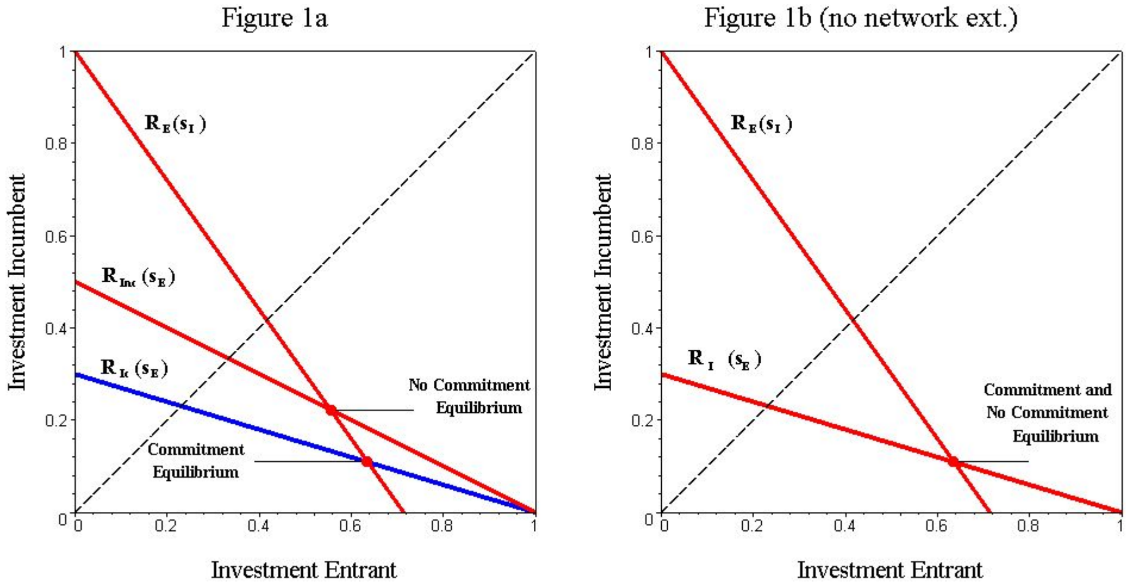

Figure 2.1: Best Response Functions - Market Outcome

2.4 Social Optimum

In the previous section we obtained the incentives to innovate in an industry that exhibits network externalities and durable goods. In particular, we considered the monopoly case and concluded that, in line with the current literature, in the absence of commitment the monopolist has incentive to invest in R&D in excess of what it would maximize its overall profits. Moreover, we showed that the negative impact of this over-investment was reflected in lower social welfare and it was a consequence of the presence of network externalities.

Subsequently, we analyzed the case where the monopolist is faced by a potential entrant. Interestingly, we were able to conclude that due to the threat of entry, the commitment problem exhibited in the monopoly case by the incumbent firm was not present anymore. Even thought the absence of commitment was reflected in higher investments because the incumbent is not able to internalize the negative impact on his period 1 pricing, the threat of entry, and the induced higher level of investment, more than compensated the lower period 1 revenues by increasing the expected period 2 profits.

However, it is important to analyze the social efficiency of the results obtained in the previous section. Therefore, and as a major objective of this chapter, the present section consider the problem faced by a social planner that maximizes social surplus. In particular, we obtain the socially optimal R&D incentives and compare our results with the ones obtained before for the case of the market outcome. Moreover, we investigate the role of network externalities in the potential social inefficiencies that may arise.

Assuming that the social planner is able to produce the two goods, set prices equal to zero, induce adoption and invest in R&D, its problem can be written as,

$$\begin{aligned}\max_{s_I,s_E} W = {} & N_1 p_1^s + s_I s_E(N_1 s_n + N_2 p_n) s_I(1-s_E)(N_1 s_n + N_2 p_n) \\ & + s_I(1-s_E)(N_1 s_n + N_2 p_n) + (1-s_I)(1-s_E)(N_1 s_o + N_2 p_o) \\ & - \frac{s_I^2}{2} - \frac{s_E^2}{2}\end{aligned} \tag{2.10}$$

with,

$$p_1^s = q_1 + \alpha N_1 - c$$

As before, we have simplified taking into account $a = 1$ $p_u = q_2 - q_1 + \alpha N_2 - c_u$, $p_n = q_2 + \alpha - c$, $p_o = q_1 + \alpha - c$, $s_n = q_2 + \alpha - c_u$ and $s_o = q_1 + \alpha$.

Equation (2.10) is obtained by calculating, for each period, the maximum social surplus that can be enjoyed by the entire population given that the social planner can induce adoption. In addition, the assumption that the social planner invests in the two technologies simply reflects a risk diversification strategy. That is, ex-ante, it is impossible for the social planner to realize which technology will be successful in period 2. Also, note that investing in both technologies is an efficient strategy given the quadratic form of the costs associated with the innovation process.

Note that for the social planner problem the SPNE and the NE coincide. Therefore, we can calculate the first-order condition that provide the socially optimal investment level. This expressions are,

$$0 = (1-s_E)(N_1 s_n + N_2 p_n) - (1-s_E)(N_1 s_o + N_2 p_o) - s_I^w \tag{2.11}$$

$$0 = (1 - s_I)(N_1 s_n + N_2 p_n) - (1 - s_I)(N_1 s_o + N_2 p_o) - s_E^w \tag{2.12}$$

As can be seen from equations (2.11) and (2.12), the social planner invests equally in both technologies. This is due to the fact that the social planner internalizes the costs of the projects. Moreover, straightforward manipulations of equations (2.11) and (2.8) show that the best response function of the social planner is identical to the one exhibit by the incumbent firm in the presence of commitment. This implies that in order to compare the social optimum with the results from the market outcome we should consider the results presented in Figure 2.1 with the level of investment produced by the incumbent's best response function in the presence of commitment. Given that the social planner invest equally in both technology, the social optimal level of investments is reached in the intersection of the incumbent's best response function with commitment and the 45 degree line. This is presented in Figure 2.2.

Figure 2.2 provides two interesting results. First, it shows that the entrant firm, unambiguously, always over-invests in R&D in relation to the socially optimal amount. That is, independent of the presence of commitment by the incumbent, the market equilibrium always lie to the right of the social optimum. This result is due to the fact that a successful innovation represents the only possibility for the potential entrant to make positive profits.

Proposition 12 *The potential entrant unambiguously exhibit an over-investment in comparison with the social optimum. This result is independent of the possibility of commitment by the incumbent firm.*

In addition, it can be observed in Figure 2.2 that in the absence of network externalities or for sufficiently low values of α the incumbent firm always under-invests in R&D. However, depending on the extent of the network externalities (i.e the value of α) the incumbent firm may exhibit a lower (Figure 2a), equal (Figure 2b) or higher (Figure 2c) level of investment compared with the social optimum. This result follows from numerical simulations.

Proposition 13 *Depending on the extent of the network externalities, the incumbent firm may exhibit a lower, equal or higher investment level in comparison with the social optimum.*

This result sheds some light on the controversy around the efficiency of the observed market structure in network industries. As has been pointed in the literature (and observed in reality), network industries are characterized by the presence of few successful incumbents. This observed structure has led regulation authorities to consider whether the high level of concentration is detrimental for the socially optimal level of innovation undertaken in these industries. Our analysis shows that there is no clear answer to that questions and that the measurement of the extent of network externalities may be crucial for policy purposes. Hence, any conclusion must be based on a formal analysis and this chapter is a small step in that direction.

2.5 Conclusions

We presented a model of R&D competition between an incumbent and a potential entrant in market with durable goods and network externalities. In particular, we analyzed the market outcome and the social efficiency of the incentive to innovate in the presence of uncertain innovation processes. The robustness of the presented results with respect to the assumed functional forms is the objective of current work.

We found three main results. First, the threat of entry reverses the commitment problem that a monopolist (without such threat) may face in its R&D decision given the durability of the network goods. This result is not present in the current literature on R&D and follows from the role that R&D incentives play in deterring entry. In our case, the monopolist's commitment problem arises only due to the presence of network externalities.

Second, the levels of R&D determined by market outcome might differ from the socially optimal levels. In particular, a potential entrant always over-invests (as an entry strategy) and an established incumbent might exhibit higher, lower or equal R&D

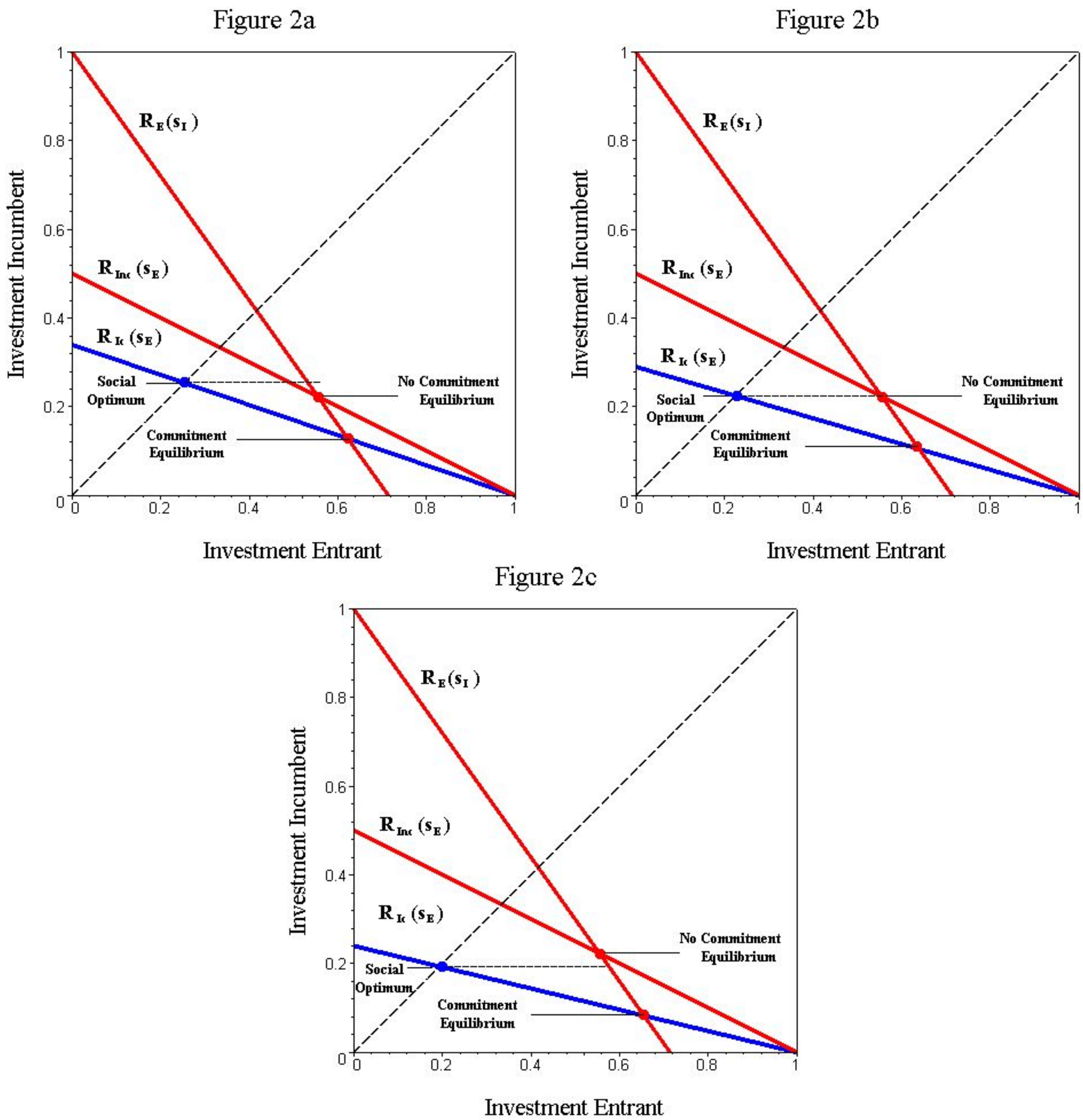

Figure 2.2: Best Response Fncs. - Social Optimum

levels in comparison with the social optimum. This result suggests that successful entry takes place too often in comparison with the social optimum.

And third, the extent of network externalities is the crucial parameter in the efficiency of the incumbent R&D level. In fact, it is only the presence of network externalities that permits, potentially, to the established incumbent to provide an efficient level of innovation. Without network externalities (or very low network effects), it is shown that the incumbent firm always under-invests in R&D efforts. This result sheds some light on the debate whether a dominant incumbent in a network industry provides sufficient innovation to the society.

We recognize several areas of further research in the area of R&D incentives in the presence of network externalities and durable goods. To reduce the dependence on initial conditions and parameter assumptions, a fully dynamic model may shed light on some more realistic characteristics of industry evolution inside the framework analyzed in current chapter. In addition, the analysis of compatibility decisions must also be considered given its obvious relevance in these industries but for the time being beyond the scope of the present chapter. Finally, a more detailed (or alternative) description of the consumers' coordination assumptions may enrich the results.

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Chapter 3

Dynamic R&D Incentives with Network Externalities[1]

3.1 Introduction

An industry exhibits network externalities when the benefit that consumers enjoy from purchasing one or several of its goods depends on the number of other consumers that use the same and/or compatible products. For the firms in those sectors (e.g. telecommunications, consumer electronics, operating systems, etc.), the presence of network externalities implies that the attractiveness of their products is a function of their quality-adjusted prices and the potential benefit attached to their expected network sizes (i.e. installed bases).[2]

As a consequence, consumers must form expectations about the future evolution of such installed bases before acquiring a network good. Anticipating the best future network is a key consideration because the costs associated with switching from one network to another could be prohibitively high. Thus, the role of installed bases and expectations are crucial for consumer choice and, even decisive, in the future of a network industry: A network technology may dominate a market only because it is

[1]This chapter extends previous joint work with Toker Doganoglu, University of Munich.

[2]See Katz and Shapiro (1985, 1986) and Farrel and Saloner (1985, 1986) for seminal treatments, and Katz and Shapiro (1994) and Economides (1996) for surveys on network markets.

expected to do so.[3] For this reason, it is not surprising that industries with network externalities are characterized by a small number of successful firms or, in some cases, only one dominant incumbent serving the entire market.

Several studies have shown how pricing considerations, as well as compatibility, entry and investment decisions are affected by the presence of network externalities.[4] Moreover, due to the presence of these externalities, firms in network industries might even follow very different rules from those observed in traditional industries.[5]

This chapter develops a fully dynamic duopoly model of quality competition and analyzes how the presence of network externalities influences industry Research and Development (R&D) incentives. In doing so, we study the consequences for industry evolution, the efficiency of the market outcome and the role of consumer expectations.[6]

Rapid technological progress derived from R&D competition is a common observation in many industries with network externalities. Technological innovations allow rivalling firms to introduce new products like interactive TV, Digital Versatile Disk (DVD), and digital imaging. In nascent industries, extensive investments in R&D are usually required to introduce new standards or dominant designs.

However, the literature on investment processes, R&D efforts and innovation initiatives in industries that exhibit network externalities is still in its early stage of development. The existing literature, in its great majority, takes the processes of R&D as exogenously given and analyzes the conditions under which an innovation is adopted. Moreover, most of the work devoted to the analysis of investment decisions with network externalities considers situations where the entrant arrives with a (exogenously given) new technology, without considering a strategic response by the incumbent to

[3]The initial success of the MS-DOS operating system is usually attributed not to any technical superiority, but to the fact that it was supported by IBM.

[4]See, for example, Gabel (1991), Besen and Farrell (1994), Katz and Shapiro (1994), Grindley (1995) and Shapiro and Varian (1999) for general analyses of the impact of network externalities on firms' strategies.

[5]While the producer of a new product in a conventional market tends to place it on the market early, differentiate the good as much as possible, protect it from imitation and charge high prices, successful producers of network goods have often done the exact opposite. See Grindley (1995).

[6]In fact, among some authors, Besen and Farrell (1994), Katz and Shapiro (1994) and Arthur (2000) have pointed out that it is the role of consumer expectations what determines the particular dynamics in industries with network externalities, in comparison with other industries under increasing returns to scale.

the threat of entry.[7]

Some of the main results of this literature are: i) new technologies tend to be adopted too early and the successful entrant remains as incumbent forever; ii) the structure of property rights (i.e. sponsorship) over a new technology affect decisively its potential for adoption; and iii) R&D incentives play no major role in affecting consumer expectations, and hence, choice. Kristiansen (1996) and Choi (1994) consider the case of endogenous investment in network industries using two-period models and analyze the riskiness associated to the R&D projects. Their results are focused on the divergence between private and social incentives to invest and show the role of network externalities in this divergence.

In this chapter, our dynamic model of quality competition with network externalities adapts the Markov-perfect equilibrium framework presented in Ericson and Pakes (1995). We depart from the current literature on network industries by focusing our analysis on three main areas. First, we consider endogenous and uncertain R&D efforts taking into account the way consumers form expectations. This allows us to analyze the incentives to innovate as a result of strategic interaction inside the industry and to explore the impact of network externalities on industry evolution. Second, we embed our analysis in a fully dynamic framework. This implies that our results are independent of initial and/or end conditions, permitting us to determine the equilibrium market structure endogenously. And third, we consider the long run social efficiency of the R&D incentives that drives the evolution of the network industry.

Specifically, we consider two firms, an established firm and a challenger, that compete each period with two incompatible technologies over an infinite horizon. To capture the role of the installed base, we assume overlapping generations of homogeneous consumers that live for two periods and make purchases (inelastically) only once when they arrive to the market. Thus, in each period the population consists of a "young" and an "old" generation of consumers.

The established firm in period t is the firm that won competition in period $t-1$

[7] See Farrell and Saloner (1985), Farrell and Saloner (1986), Katz and Shapiro (1986), Katz and Shapiro (1992), De Bijil and Goyal (1995), Shy (1996), Fudenberg and Tirole (2000), among others.

("young" consumers bought from it) and exhibits an installed base in period t ("old" consumers cannot make another purchase). In addition, both firms offer a technology, whose quality can be improved through endogenous and uncertain R&D efforts. At each t, a firm invests in order to develop, with positive probability, an improvement of its quality for period $t+1$. For simplicity, we assume that R&D outcome is either a success or a failure and, if it is successful, it increments the value of the quality by a fixed amount.

Moreover, we consider the case of R&D competition outside the industry. This situation can be interpreted as the role played by independent research facilities, universities, etc. In our framework, the role of outside competition implies that with an exogenous probability, there is the possibility that in a given period the relative quality of a network good is reduced. Therefore, our model captures the idea of quality competition in a market facing competitive pressure from within and outside the industry. Given that competition takes place each period depending on the level of quality of the good produced by the two firms, which in turn depends on the stochastic R&D processes, the drivers of industry evolution are the investment incentives of the competing firms. This setup allows us to compare our results with important existing work on the interplay between R&D and competition.

The model is solved in two steps. In the first step, the product market competition observed in each period is determined considering the expectation formation process. For any given quality state (i.e. quality levels of the two firms), the equilibrium prices and per-period profits are computed, allowing us to see the impact of network externalities on consumers' behavior. In the second step, given the outcome of the product market competition, the fully dynamic investment decision problem is stated and solved numerically using the methodology developed by Pakes and McGuire (1994). Equilibrium occurs when the two firms' expectations about their competitors strategies are consistent with their actual behavior.

We show four main results. First, the presence of network externalities generates important incentives to invest in R&D in order to innovate. These investment levels are higher than the levels that would be observed without network externalities due in part to the role of consumer expectations. This result has three important implications: i) with a positive probability, the traditional result of "monopolization" in one network technology can be overcome, resembling the industry evolution of temporary monopolists; ii) the threat of losing the market induces the established firm to follow R&D projects in order to reduce the probability of being overtaken by the challenger; and iii) the challenger firm has enough incentives to try to overtake the market. These implications are in clear contrast with the current literature that predicts that successful firms remain as incumbents forever.

Second, for high network effects, a high level of outside competition implies higher investment levels. This result implies that the relation between innovation incentives and the level of competition is not an inverted U-shaped function, as traditional innovation theory for non-network industries suggests, but it is a monotone increasing function when network effects are important. This result says that the expectation of exhibiting future installed bases is so strong, that even considering the case of being a technological laggard, higher investment levels are, on expectation, worth pursuing. In addition, this result rationalizes the observed high technological competition in network industries.

Third, we analyze the incentives to innovate for both firms, we compare the outcome with the social optimum and investigate the role of the network externalities in the potential inefficiencies. We find that the market tends to over-invest in R&D in comparison with the level that maximizes social surplus. This implies that introduction of new incompatible technologies occurs too often in equilibrium.

And fourth, with high competition outside the industry, the extent of network externalities is critical in determining the size of the inefficiency associated with the investment levels. This result shows that in the presence of high outside R&D competition, the inefficiency associated with the investment level is minimal when network externalities are not present. As network effects become more important, the inefficiency is increased monotonically. This results permits to see a clear impact of the role of network externalities in determining innovation incentives and the associated social efficiency.

The chapter is organized as follows. The next section presents the model. Section 3 presents the analysis of its equilibrium. Section 4 discusses the main results. Finally, section 5 concludes and discusses some areas of further research.

3.2 The Model

We present a model of duopoly competition in a market that exhibits network externalities. Time evolves discretely over an infinite horizon in order to avoid end effects. Both firms produce with identical marginal costs but potentially different qualities. Consumers are assumed to be homogeneous in an overlapping generations structure.

3.2.1 Supply Side and R&D Process

There are two firms in the industry producing network goods. Let $f \in F = \{0, 1\}$ denote the identity of the firms, where 0 represents a firm that lacks an installed base and 1 represents the firm with an installed base.[8] It is assumed that goods produced by different firms are mutually incompatible. That is, the size of the network associated with a given firm is equal to the number of users of the good produced by that firm. For simplicity it is assumed that marginal and fixed costs of production are equal to zero.[9]

At any period t, each firm exhibits a given quality embedded in the network good it produces. This quality level is indexed by i and is independent of the network benefits that the good may provide. In order to simplify exposition, it is assumed that this level of quality is relative to an outside technology.[10] This assumption serves two purposes. First, it allows us to focus on a smaller set of possible qualities (i.e. relative qualities),

[8] As will be explained below, the assumption of homogeneous consumers imply that in each period only one firm captures the entire market. This fact means that at the beginning of each period, one firm ($f = 1$) exhibits an installed base (i.e. captured the market the previous period), while the other firm has no such base ($f = 0$).

[9] A linear demand specification guarantees that this assumption is without loss of generality.

[10] The outside technology can be thought as a technology that is publicly available to firm f and is produced in, for example, universities or research facilities. Formally, if the actual quality state of the technology produced by firm f is i^* and the outside technology available to this firm is i^{out}, then $i = i^* - i^{out}$.

and second, it provides an upper limit to the per-period profits of the firms. This latter condition is required for the existence of the equilibrium. For simplicity, it is further assumed that the outside technology does not provide any network benefit.

In our duopoly setup, we denote the competitor of firm f and its quality level by f_- and j, respectively. Therefore, a firm in the industry can be fully described by its state (i, j, f).[11] We consider $i, j \in Q$, where Q is the quality space and $f \in F$. For simplicity, we analyze the case of $Q = \{1, 2, 3\}$. That is, there are only three possible (relative) quality levels that can be exhibited by a firm.[12]

Qualities evolve stochastically over time. This evolution depends on the firm's own costly R&D efforts and on the developments of the outside technology. Specifically, firm f's own technology is improved with a probability that depends positively on its investments. Let x_f denote the investment level on R&D of firm f. We take the probability that firm f improves its quality to be $\frac{x_f}{1+x_f}$, while the outside technology is assumed to be improved each period with probability δ.

Hence, if $\mathrm{p}(i'|i, x_f)$ denotes the probability that firm f will have quality i' in $t+1$ given that it has quality i and invests x_f in t, we have,

$$\mathrm{p}(i'|i, x_f) = \begin{cases} \frac{x_f}{1+x_f} & \text{if } i' = i+1 \\ \frac{1}{1+x_f} & \text{if } i' = i \end{cases}$$

if $i = 1$,

$$\mathrm{p}(i'|i, x_f) = \begin{cases} \frac{(1-\delta)x_f}{1+x_f} & \text{if } i' = i+1 \\ \frac{1-\delta+\delta x_f}{1+x_f} & \text{if } i' = i \\ \frac{\delta}{1+x_f} & \text{if } i' = i-1 \end{cases}$$

if $i = 2$, and

[11] Note that (i, j, f) actually describes the state of the industry because for every (i, j, f) there is a corresponding (j, i, f_-). This formulation will allow us to focus on a symmetric equilibrium.

[12] Note that the actual quality, the numerical value, is not defined yet.

$$\mathrm{p}(i'|i,x_f) = \begin{cases} \frac{1-\delta+x_f}{1+x_f} & \text{if } i'=i \\ \frac{\delta}{1+x_f} & \text{if } i'=i-1 \end{cases}$$

if $i = 3$. As can be seen, this formulation implies that a given level of quality evolves only one step (up or down) from period to period. We now explain the details of the demand side.

3.2.2 Demand Side and Expectation Formation Process

At any period t, there are two overlapping generations of consumers that live for two periods. Each period a mass of 1 "young" consumers arrives into the market and join a mass of 1 "old" consumers, so the total population each period is constant and equal to 2. Consumers are assumed to be homogeneous with an inelastic demand for a single unit of the network goods offered by the firms. Upon arrival consumers observe the state of the industry (i.e. they observe (i, j, f) and the corresponding (j, i, f_{-})), investments, prices and, then, purchases take place. This process is explained below.

It is important to note that the assumption of homogeneous consumers imply that in each period only one firm captures the new generation of "young" consumers. Moreover, once a firm captures the market, it will exhibit an installed base in the next period because "old" consumers are locked-in. Therefore, at the beginning of each period there is one firm with an installed base (i.e. $f = 1$) and one firm without it (i.e $f = 0$).

Note that consumers buy a durable network good only once, which amounts to say that they exhibit prohibitively high switching cost, and therefore, they will be locked-in in the second period of their lives with the network good that they bought in their first period. In addition, note that before purchase takes place, consumers observe the investments undertaken by the competing firms, and thus, the strategic role of the investment decision is two-fold: i) to affect future quality; and ii) to influence directly consumers' expectations about the future installed base.

Importantly, in the presence of network externalities, a consumer decision depends on how other consumers are deciding. Therefore, consumers must form expectations about other consumers behavior. In our setup, this expectation formation process has two dimensions. First, consumers arriving in the market in period t must also care about how the other consumers also arriving in t decide (i.e. my utility is higher, the more consumers in my own generation choose a compatible good). Second, given that consumers are locked-in when they are "old", consumers arriving in period t must care about the choice made by the new generation of "young" consumers arriving in $t + 1$ (i.e. my utility is higher, the more next generation consumers choose a compatible good). Moreover, consumers arriving in t care about the choice of consumers arriving in $t + 1$, which in turn care about the choice of consumers in $t + 2$, and so on.

Therefore, in order to calculate demand, the process under which consumers form expectation must be determined in a way that is consistent with a dynamic equilibrium. We propose the following two-step expectation formation process. In the first step, concerning the behavior among individuals of the same generation, we assume that the consumers behave as "optimal coordinators". That is, consumers decide assuming that all their contemporaries are able to identify and coordinate on the Pareto-optimal choice.[13]

In the second step, concerning the expectations on the behavior of future consumers, we assume that if in a given period the two competing goods exhibit the same quality, the good provided by the firm with an installed base is preferred. In the case of quality differences, the good with the higher quality is going to be favored. We assume that consumers in t follow this rule and expect future consumers to follow it. As will be shown below, this rule is consistent with equilibrium behavior.

Now that the demand and supply side have been explained, and before we state formally the product market competition, as well as the firms' dynamic problem, we present the time structure. Specifically, at each period t events develop as follows,

- (Relative) quality values are realized
- Firms invest to improve quality
- Prices are determined

[13] See Katz and Shapiro (1986), and Farrell and Katz (2005).

- Consumers arrive and observe the current quality state, investments and prices
- Purchases take place

3.2.3 Product Market Competition

In each period, a firm finds itself in state (i, j, f), where i is the (relative to an outside good) quality state of the good it produces, j is the quality state of the competing firm, and f is the identity of the firm according to the installed base.[14] As we explained before, consumers are homogeneous implying that only one firm captures the the entire market each period. We assume that firms are engaged in price (Bertrand) competition in the product market. Therefore, given our expectation formation process assumptions, we calculate the maximum utility that a consumer may enjoy from each of the two network goods, compare them and derive the corresponding equilibrium demands and prices.

Specifically, the benefit enjoyed by a generation of consumers arriving in the market in a given period and buying from the firm with the installed base ($f = 1$) is given by,

$$\begin{aligned} u_i^1 = a_i + 2\omega + \beta\Big[&(1-\delta)a_i + \delta a_{i-1} \\ &+ \omega(1 + 1\cdot \mathrm{p}(i' > j'|i,j) + 1\cdot \mathrm{p}(i' = j'|i,j))\Big]. \end{aligned} \tag{3.1}$$

In this expression, the first two terms represent the utility enjoyed by the consumer in his first period when is "young". In particular, a_i represents the actual value of the quality level (given state i) and 2ω represents the network benefits. Recall that the quality values are relative to an outside option from competition outside the industry. Moreover, equation (3.1) implicitly says that the outside option is not a network good from a consumer's perspective.[15]

[14] Again, note that a state (i, j, f) imply that the competitor is in state (j, i, f_-).

[15] This is the case, for example, of free software available on the internet. A consumer deciding to buy a software, may consider free software as a benchmark of quality without caring too much about the network benefits it provides.

Note that the expression presented in equation (3.1) is the utility derived from the consumption of the good provided by the firm with an installed base. Therefore, in this case the entire population would be consuming the good from firm $f = 1$ and the network benefits is two times the valuation ω of those network benefits (i.e. 2ω).

The third term corresponds to the utility derived in the second period when the consumer is "old", where β is the discount factor. Given that the consumer is locked-in with his first period choice, in the his second period he will enjoy the same good with a quality value that depends on the evolution of the outside option. That is, with probability $(1-\delta)$ the outside technology does not advance and therefore he enjoys the same quality level, while with probability δ that advance takes place and the quality is reduced.

In terms of the network benefits enjoyed in his second period, it is clear that they depend on the choice made by the new generation. Therefore, according to our expectation rule (i.e. better quality firm captures the market or established firm does if qualities are equal), it can be presented as follows. The network benefits are weighted by the parameter ω that multiplies: i) the first term represent the network benefits derived by the fact that the consumer is locked-in in the second period; and ii) it will enjoy and extra generation if the technology adopted captures the market in the next period. This occurs with probability $\mathrm{p}(i' > j'|i,j) + \mathrm{p}(i' = j'|i,j)$, where i is the quality exhibit by firm $f = 1$ and j is the quality of its competitor in the current period. i' and j' represent the quality values in the next period for $f = 1$ and the competitor $f = 0$, respectively.

Analogously, we can describe the utility derived if the given generation of "young" consumers decides to purchase from the competing firm $f = 0$. The interpretation follows the same lines as in the previous case.

$$
\begin{aligned}
u_j^0 = a_j + \omega + \beta \Big[& (1-\delta)a_j + \delta a_{j-1} \\
& + \omega(1 + 1 \cdot \mathrm{p}(i' < j'|i,j) + 1 \cdot \mathrm{p}(i' = j'|i,j)) \Big].
\end{aligned}
\tag{3.2}
$$

It can be shown that $i \geq j$ implies that the expression in equation (3.1) is greater than the one in equation (3.2). This result is important in order to work with an expectation rule that is dynamically consistent.

Given the homogeneity of the consumers, the demand function for each generation of "young" consumers is described as follows. Suppose f represents the firm that exhibit the installed base and i its quality, then, demand (the identity of the firm the "young" consumers buy from) as a function of the current state (i, j, f) is given by,

$$\mathrm{D}(i, j, f) = \begin{cases} f & \text{if } i \geq j \\ f_{-} & \text{if } i < j \end{cases}$$

Under our assumption of Bertrand price competition, equilibrium prices are described as follows. Again, suppose f represents the firm that exhibit the installed base and i its quality,

$$\mathrm{p}^*(i, j, f) = \begin{cases} \overline{a}_i + \omega + \beta \Big[a_i - a_j + \omega(\mathrm{p}(i' > j') - \mathrm{p}(i' < j')) \Big] & \text{if } i \geq j \\ \overline{a}_j - \omega + \beta \Big[a_j - a_i + \omega(\mathrm{p}(j' > i') - \mathrm{p}(j' < i')) \Big] & \text{if } i < j \end{cases}$$

Where $\overline{a}_i = (1-\beta\delta)(a_i - a_j) + \beta\delta(a_{i-1} - a_{j-1})$ and $\overline{a}_j = (1-\beta\delta)(a_j - a_i) + \beta\delta(a_{j-1} - a_{i-1})$.

Given that each period the mass of new consumers is equal to 1, the per-period profits $\pi(i, j, f)$ that result from product market competition equal the optimal Bertrand prices just presented (i.e. $\mathrm{p}^*(i, j, f) = \pi(i, j, f)$). Note that the determination of $\mathrm{p}^*(i, j, f)$ implicitly says that firms cannot price below zero. Given that marginal costs are equal to zero, this would be equivalent to negative mark-ups. However, the case of possible negative mark-ups is not considered. Even though it could be an interesting extension, negative mark-ups are associated with predatory pricing which is illegal and complicates greatly the model.

As can be seen from the price equilibrium expression, the profits obtained in period t depend on the expected qualities that are going to be realized in period $t+1$, which in turn depends on the investment decisions by the two firms. Thus, in order to solve for the product market competition in t, we need to solve the dynamic problem that determines the distribution of $t+1$ qualities (i.e. equilibrium investments). In this way, we see how equilibrium prices are derived from dynamic incentives due to the role of investment decisions in affecting consumers choice. In order to do this, we need to state the dynamic problem using the following Bellman equations.

3.2.4 Dynamic Setup

Let $V(i,j,f)$ denote the expected net present value to firm f when its quality level is given by i and the quality level by its competitor is given by j. In what follows, we first characterize the value function $V(i,j,f)$ under the presumption that the firm behaves optimally. In a second step, we derive the policy function $x(i,j,f)$. Throughout we take the competitor firm's investment strategy as given.

The Bellman equation is,

$$V(i,j,f) = \sup_{x \geq 0} \left[\pi(i,j,f) - cx + \beta \left[\sum_i \sum_j \sum_f V(i',j',f') p(f') p(j') p(i') \right] \right],$$

where $0 < \beta < 1$ is the discount factor and c represents the marginal cost of investment. The Bellman equation adds the firm's current cash flow $\pi(i,j,f) - cx$ and its discounted expected future cash flow.

Importantly, note that given our demand specification, a firm that captures the market today becomes, unambiguously, the established incumbent tomorrow. Therefore, for $f = 1$, $i \geq j$ implies $f' = 1$ and $f' = 0$, otherwise. Analogously, for $f = 0$, $i > j$ implies $f' = 1$ and $f' = 0$, otherwise. This allows us to simplify the Bellman equations as follows,

$$V(i,j,1) = \sup_{x \geq 0} \left[\pi(i,j,1) - cx + \beta \left[\sum_i \sum_j V(i',j',1) p(j') p(i') \right] \right],$$

whenever $i \geq j$ (i.e. a firm with an installed base is able to maintain its dominant position).

$$V(i,j,1) = \sup_{x \geq 0} \left[\pi(i,j,1) - cx + \beta \left[\sum_i \sum_j V(i',j',0) p(j') p(i') \right] \right],$$

if $i < j$ (i.e. the established firm loses its dominance).

$$V(i,j,0) = \sup_{x \geq 0} \left[\pi(i,j,0) - cx + \beta \left[\sum_i \sum_j V(i',j',1) p(j') p(i') \right] \right],$$

if $i > j$ (i.e. the firm without the installed base captures the market). And finally,

$$V(i,j,0) = \sup_{x \geq 0} \left[\pi(i,j,0) - cx + \beta \left[\sum_i \sum_j V(i',j',0) p(j') p(i') \right] \right],$$

if $i \leq j$ (i.e. the challenging firm keeps competing without an installed base).

Note that, for a given i' and f', we can define $W_1(i') = \sum_j V(i',j',1)p(j')$ and $W_0(i') = \sum_j V(i',j',0)p(j')$ as the expected state of the competitor. Thus, the general expression for the Bellman equation can be written as,

$$V(i,j,f) = \sup_{x \geq 0} \left[\pi(i,j,f) - cx + \beta \left[\sum_i W_{f'}(i') p(i') \right] \right], \tag{3.3}$$

where,

$$f' = \begin{cases} 1 & \text{if } f = 1 \text{ and } i \geq j \\ 0 & \text{if } f = 1 \text{ and } i < j \\ 1 & \text{if } f = 0 \text{ and } i > j \\ 0 & \text{if } f = 0 \text{ and } i \leq j \end{cases}$$

Note that $W_{f'}(i')$ is the expectation over all possible future states calculated under the presumption that firm f invests $x(i,j,f)$, and its competitor, firm f_{-}, invests $x(j,i,f_{-})$. In addition, $W_{f'}(i')$ is all that firm f needs to know in order to compete in the market.

3.2.5 Investment Strategies

The first-order condition (FOC) for an interior solution is,

$$\frac{\partial \pi(i,j,f)}{\partial x_f} - c + \beta \sum_i W_{f'}(i') \frac{\partial p(i')}{\partial x_f} = 0. \tag{3.4}$$

for,

$$f' = \begin{cases} 1 & \text{if } f = 1 \text{ and } i \geq j \\ 0 & \text{if } f = 1 \text{ and } i < j \\ 1 & \text{if } f = 0 \text{ and } i > j \\ 0 & \text{if } f = 0 \text{ and } i \leq j \end{cases}$$

Consider $i = 2$ as a general case. It can be shown that the second-order condition is satisfied whenever a solution to equation (3.4) exist. Moreover, the equilibrium investment level is the maximum between zero and the value of x that solves equation (3.4).

3.2.6 Equilibrium

As we explained before, given that each firm, and therefore the industry, can be totally described according to the state (i, j, f), this allows us to focus attention to symmetric Markov-perfect equilibria (MPE) as defined by Maskin and Tirole (1988). This concept selects those subgame-perfect equilibria where actions are a function only of pay-off relevant state variables, and thus eliminates many of the vast multiplicity of subgame-perfect equilibria that would normally exist in this type of model. Firms maximize their expected discounted value of profits conditional on their expectations of the evolution of competition. Equilibrium occurs when the two firms' expectations are consistent with the process generated by the optimal policies of their competitors.

Proof that equilibrium exists has been shown in the literature. The proof is omitted both because it would replicate previous work and because such a proof would be redundant given that our approach in this chapter is to solve numerically for equilibrium once the parameters of the model are defined. In the event that the numerical algorithm converges, that is sufficient for existence of equilibrium for a specific set of parameters.[16]

A much greater problem of this kind of models is the potential multiplicity in the number of equilibria. This is the reason for choosing to focus on a symmetric equilibrium. That is, two firms that are at identical states are restricted to follow the same strategies. In our setup, this amounts to say that if firm f is in state (i, j, f), he expects his competitor f_- to behave in the same way as firm f would behave being in state (j, i, f_-). This assumption is standard in the literature of Markov perfect games and serves also to simplify greatly the computational burden of the model. We also check the multiplicity of equilibria by allowing the numerical algorithm to start from different initial conditions. No case was identified where there was more than one equilibrium.[17]

3.2.7 Computation

To compute the symmetric MPE, we use a variant of the algorithm described in Pakes and McGuire (1994). The algorithm works iteratively. It takes a value function $\widetilde{V}(i, j, f)$ and a policy function $\widetilde{x}(i, j, f)$ as its input and generates updated value and policy functions as its output. Each iteration proceeds as follows: First, we use equation (3.4) to compute a firm f's investment strategy $x(i, j, f)$ taking the other firm's investment strategy to be given by $\widetilde{x}(j, i, f_-)$. In doing so, we use $\widetilde{V}(i, j, f)$ and $\widetilde{x}(j, i, f_-)$ to compute $W_{f'}(i')$. Second, we compute the payoff $V(i, j, f)$ associated with firm f using $x(i, j, f)$ and $W_{f'}(i')$. The iteration is completed by assigning $V(i, j, f)$ to $\widetilde{V}(i, j, f)$ and $x(i, j, f)$ to $\widetilde{x}(i, j, f)$. The algorithm terminates once the relative change in the value and the policy functions from one iteration to the next are below a pre-specified level of tolerance. All programs are written in Matlab 6.5 and are available upon request.

[16]Convergence of the numerical algorithm is a sufficient condition for the existence of a ε-equilibrium. See Benkard (2004).

[17]Similar approaches to analyze industry evolution are presented in Besanko and Doraszelski (2004), Benkard (2004), and Doraszelski and Markovich (2005).

3.2.8 Parametrization

We consider a time period as a year and calculate the discount factor, β, from an interest rate of approximately 8%. This implies a discount factor of $\beta = 0.925$. Even though the parameter of the marginal cost of investment, c, affects in an important way the long term behavior of the industry, the qualitative results tend to be maintained. For simplicity, we assume $c = 1.0$.

The parameter that measures the probability of exogenous innovation is perhaps the most influential parameter in our results. Given that no empirical estimation of this parameter is available for the case of a network industry, the results presented in this chapter consider $\delta = 0.1$, $\delta = 0.4$ and $\delta = 0.7$. We believe that, as has been widely highlighted, network goods are based on very fast-paced innovations, the value of $\delta = 0.1$ is not very realistic. However, in order to present a general analysis the case of $\delta = 0.1$ is considered, but the focus is on $\delta = 0.4$ and $\delta = 0.7$.

We assume that the values of the qualities are equal to 0, 1 and 2 for the cases of i equal to 1, 2 and 3, respectively. Given the role of the outside option, it is natural to normalize to 0 the lower possible relative quality. It is assumed that $0 < \omega < 1$. This assumption is important to maintain the consistency of the expectations rules explained above.

We recognize that the potential relevance of the conclusions provided in this chapter are still to be corroborated by empirical analysis of network industries.

3.3 Results

In this section we present the results we obtained for our model of duopoly competition under network externalities and endogenous and stochastic R&D processes. We first report some results on the incentives to innovate by analyzing the optimal investment levels exhibited by the two firms. We analyze these results and observe how they depend on the relevant parameters (i.e. marginal cost of investment, probability of exogenous innovation and extent of network externalities). Subsequently, given that our industry is described by a markov chain, we use the well-developed literature on stochastic processes to analyze the long term behavior of this industry. By doing this, we are able to determine the relevance of the investment level observed in each state. Finally, we compute the social optimum solution (i.e. by consider the monopolist problem and setting prices equal to zero), compare the results with the market outcome and present some results on the long run social efficiency of the evolution of the industry.

3.3.1 R&D Incentives

From equations (3.1) and (3.2) can be seen that without network externalities (i.e. $\omega = 0$), the model reduces to a dynamic quality competition with homogeneous consumers. In that case, any divergence observed in the investment decisions by the two firms are solely due to differences in their quality levels. We first look at the case without network externalities and then we compare the results with the case where network externalities are present (i.e. $\omega > 0$). By doing this, we can develop the main intuition behind the incentives to invest in R&D as a function of the quality levels. Moreover, that will allow us to observe more clearly the influence of network externalities on the R&D incentives of the firms.

Figure 3.1 presents the equilibrium investment levels exhibited by firm f as a function of its own quality level, the quality of its competitor, the probability of exogenous outside innovation (i.e. δ) and the marginal cost of investment (i.e. c). Note that in the absence of network externalities, both firm exhibit a symmetric investment schedule (i.e. equal states imply equal strategic actions).

This figure highlights two main features of the model that will be important, in particular the second, in understanding the impact of network externalities. First, the investment levels are, for any parameter values, decreasing in their marginal costs. The intuition is straightforward.

Second, the investment levels behave non-monotonically to variations in the level of the probability of exogenous outside innovation δ. In particular, the investment levels tend to follow an inverted U-shaped trajectory. Recall that δ represents the potential exogenous decrease in the firm's own relative quality level. This implies that the level of investments inside an industry are related, non-monotonically, to the speed at which

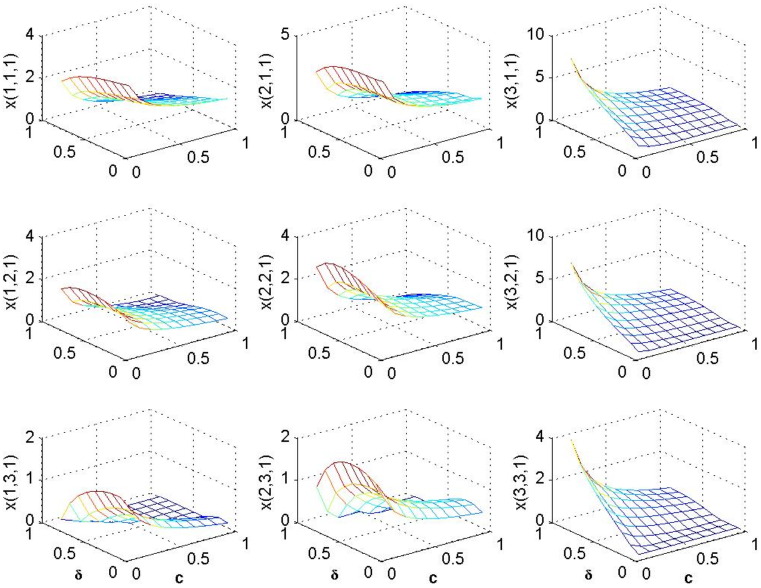

Figure 3.1: Market Outcome - Investment Levels ($\omega = 0.0$)

the industry evolves.[18]

The importance of the parameter δ is more clearly seen in Figure 3.2. This figure shows the investment levels of a firm as a function of its own quality level and that of its competitor. The left panel shows the case of $\delta = 0.4$. Clearly, with slow outside technological progress, a firm with a low quality level has a strong incentive to improve its quality and reap the profits associated with a better product. However, once a high level of quality is reach, the incentives to keep investment are reduced because the better quality is more likely to be maintained. It can be shown that these incentives are reduced in the presence of higher marginal costs of investment.

Analogously, the right panel shows the case of $\delta = 0.7$. In this situation of strong outside innovation, the relative quality advantages acquired through investments are very fragile. As a consequence, a firm with a lower quality has low incentives to innovate because the expected profits associated with the achievement of a quality improvement, do not compensate the cost involved. As can be seen, a firm that already achieved a

[18]This result is reminiscent of the inverted U-shape relation between the level of competition in an industry and the incentives to innovate found in Aghion et. al (2005).

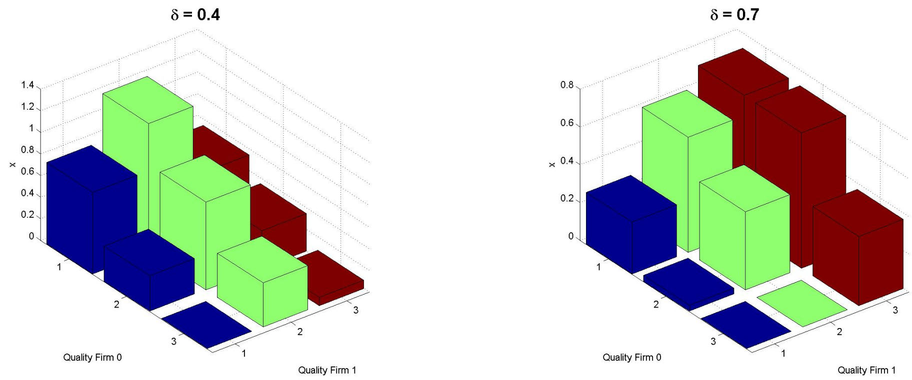

Figure 3.2: Market Outcome ($f = 1$) - Investment Levels ($\omega = 0.0$)

high advantage enjoys a dominant position and, therefore, defend that position with high levels of investment.

In addition, the impact of higher outside competition without network externalities also implies lower level of investment. According to our choice of parameters, a firm invests 0.49 on average when is faced by low outside competition represented by $\delta = 0.4$. On the other hand, for $\delta = 0.7$ suggesting an important outside pressure, the average investment can be shown to be 0.34.[19] Analogously, the impact of higher outside competition is also reflected in the average per-period profits. These values can be shown to decline from 0.76 to 0.70 as the outside competition δ is increased from 0.4 to 0.7. As standard IO theory predicts, in the presence of high competition innovation should decline, as more competition reduces the monopoly rents that reward successful innovators.[20]

From Figure 3.2 can also be seen the negative impact that a competitor relatively quality has on a firm's investment level. This situation, together with the results for high levels of outside innovation, δ (i.e. low innovation from low quality firms), suggests that the industry might be dominated for a long period by a single firm.

[19] A proper measure of the overall investment level would weight each investment level associated with a given quality state, by the steady state probability that in the long run the firm is in that state. This is done in the next subsection.

[20] See Dasgupta and Stiglitz (1980) and also the first generation of Schumpeterian growth models in Aghion and Howitt (1992), and Caballero and Jaffe (1993). Reinganum (1989) presents a survey of the literature.

Impact of network externalities. In particular, we show four main results. First, in the presence of network externalities, as with the case without them, the investment levels behave non-monotonically (i.e. inverted U-shaped trajectory) with respect to the probability of outside innovation. Second, the incentives to innovate are unambiguously increased by the presence of network externalities. Third, the increase in the investment levels is not symmetric between the two firms. And fourth, The overall impact on investments seems to depend on the level of δ. This last result requires the analysis of the long run performance of the industry and, therefore, is not analyzed in this subsection.

Figures 3.3 and 3.4 show the first result. These figures present the equilibrium investment levels exhibited by firm $f = 1$ and $f = 0$, respectively, for the case of $\omega = 0.4$. As before, these figures show the equilibrium investment levels as a function of the firm's own quality, the quality of the competitor, the probability of exogenous outside innovation, δ, and the marginal cost of investment, c. The main results hold, namely, investments are negatively related to marginal costs and non-monotonically (i.e. in an inverted U-shaped fashion) related to the probability δ of exogenous innovation.

To see in more detail the influence of network externalities, consider Figure 3.5. This figure shows the level of investment for the two firms for the case of $\delta = 0.4$. As can be seen, the figures in the diagonal represent states where the quality of both goods is equal. As expected, for the case of no network externalities (i.e. intersection with the y-axis) and equal qualities, the incentives to innovate are symmetric for both firms. Moreover, the figure shows the second result highlighted above. That is, investments increase as the network externalities become more important. This result highlights a feature frequently observed in network industries, namely, the high R&D competition as a mean to maintain an installed base.

Interestingly, note that for cases when the quality states is $(2, 3)$ or $(3, 2)$ the curves of the investment levels of the two firm intersect each other. Moreover, according to our assumptions on the demand side, a firm with a higher quality captures the market. These two figures show that with a moderate outside competition ($\delta = 0.4$) and high network effects, the winning firm may invest very aggressively in order to protect its

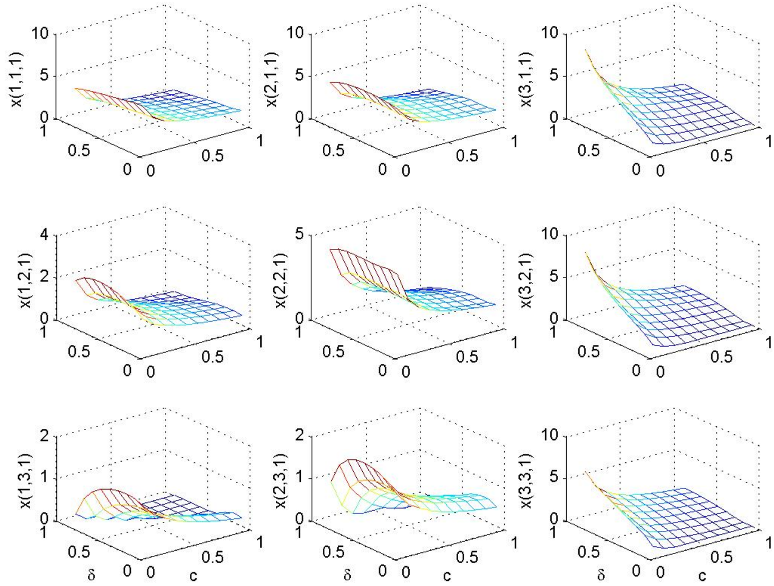

Figure 3.3: Market Outcome ($f = 1$) - Investment Levels ($\omega = 0.4$)

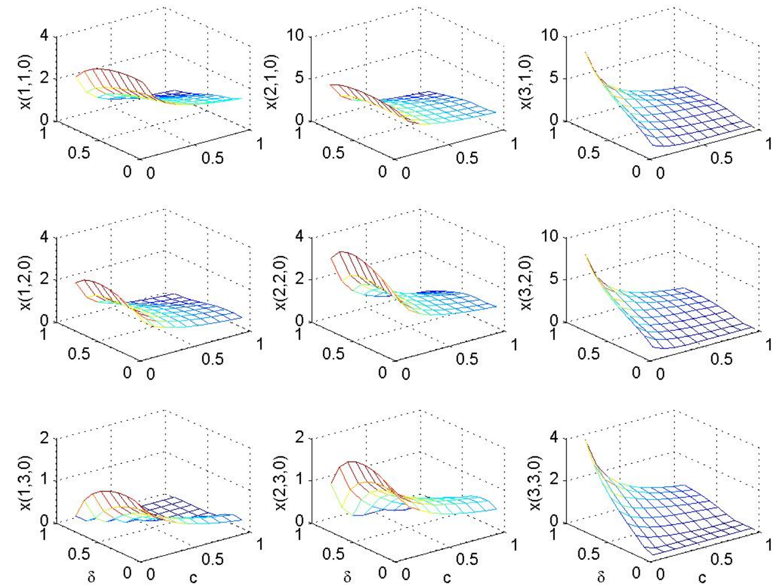

Figure 3.4: Market Outcome ($f = 0$) - Investment Levels ($\omega = 0.4$)

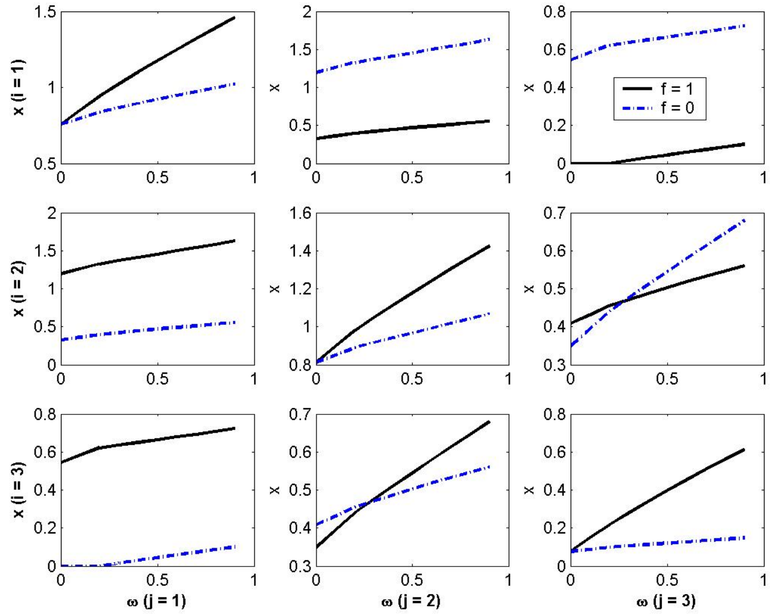

Figure 3.5: Market Outcome - Investment Levels ($\delta = 0.4$)

installed base. This situation does not hold with $\omega = 0$ and highlights the role of the expected future installed base in determining current R&D incentives.[21]

In can also be seen from the picture that the impact of network externalities affects firms in an asymmetric way. This highlights our third result. This suggests that, in the presence of network externalities, the expectation of potential gains for being the winning firm and exhibit an installed base, impacts positively the incentives to innovate of both firms. However, the expected gains tend to be higher for the firm that currently exhibits an installed base and, therefore, is that firm the one that invests more in R&D.

Finally, the fourth result states that the expected overall level of investment depends on the level of outside competition faced by the two firms. This point will be treated in the next subsection but, essentially, it shows that for high network effects the expected investment levels tend to reverse the nature of the impact of high outside competition that is observed without network externalities (i.e. the inverse U-shaped

[21]It should be notice that when the outside competition is fierce (i.e. $\delta = 0.7$) the two curves do not intersect anymore. However, the case presented shows a situation when the presence of important network benefits affect in an important way the incentives to innovate.

relation between the incentives to innovate and the level of competition).

Here we have shown that the optimal investment level of a given firm decreases with the cost of investment and with the investment level of the competitor. In addition, for high values of the exogenous advance (i.e. δ), investment levels tend to be concentrated on the high quality states. Conversely, for low values of δ, investments tend to be concentrated on low quality states. Network externalities tend to impact positively the levels of investment, but the effect between firms is asymmetric (i.e. related to the presence of installed bases). However, the long run impact depends on the relative importance of each state. This is analyzed in the next subsection when the equilibrium long term probability distribution of the quality states is calculated.

3.3.2 Industry Dynamics

Given that the investment levels determine the probability of reaching a higher quality level, they impact decisively the long term performance of the industry in a markov fashion. In order to see this, we compute the transient and the limiting distribution of the stochastic process associated with the evolution of the industry.

Given an initial state, the transient distribution determines the probability of being in any other state after a prespecified number of periods. This distribution is defined as follows. For M possible states, let P be the $M^2 \times M^2$ transition matrix of the markov process of industry evolution that can be computed using the equilibrium investment levels. Then, the marginal (transient) distribution after T periods is given by $a^{(T)} = a^{(0)} P^T$, where $a^{(0)}$ is the $1 \times M^2$ initial distribution.

In addition, the limiting distribution describes the steady state behavior of the industry. It shows the invariant probability that, for any initial state, in the long run a firm will find itself in any particular state and is defined as follows. The $1 \times M^2$ limiting distribution π, is the distribution that solves the system of linear equations $\pi = P\pi$, where P is the $M^2 \times M^2$ equilibrium transition matrix.

In our model, the transition to the steady state is very fast. That is, after a few number of period the transient distribution is equal to the limiting distribution. This situation can be due to the fact that in the model, the firm with a better quality

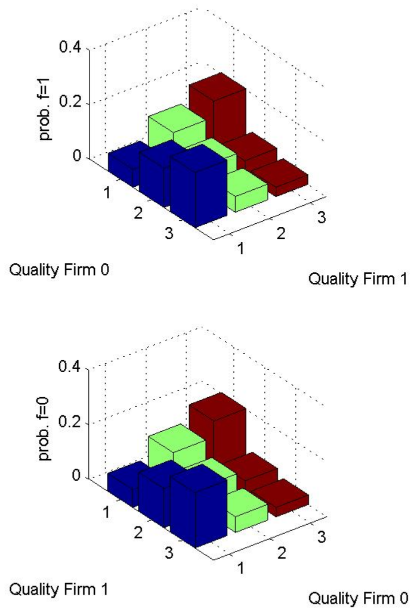

Figure 3.6: Limiting Distribution - $\omega = 0.0$ and $\delta = 0.4$

captures the entire market in only one period and there are only 3 different quality levels. However, the values of the limiting distribution depend on the initial conditions considered. As presented before, for low probability of exogenous innovation (i.e. low δ) investments tend to be concentrated in low quality states. Conversely, for high values of δ, investments tend to be concentrated in low quality states.

Let's consider $\delta = 0.4$ as a baseline. In the steady state, independent of the starting point of the industry, the limiting distribution represents the probability of being on a given state.

We briefly present the limiting distribution for the case of no network externalities (i.e. $\omega = 0$) as a benchmark for comparison. This distribution is presented in Figure 3.6. Form this figure two results can be deduced concerning the long term behavior of the industry. We denote the possible states by (i, j) and (j, i) for a firm and its competitor, respectively. Recall that the identity of the firm in the absence of network externalities is irrelevant.

First, the most likely states are those with the highest quality differentiation. That is, states $(3,1)$ and $(1,3)$. The mechanism behind this result can be described as follows. Given that the only source of differentiation between the two firms is the quality level, higher quality provides a higher profit only if the competitor exhibit a lower quality, otherwise price competition drives industry profits to zero. Therefore, once a state with asymmetric quality levels is reached, the firm with the higher quality has strong incentive to improve or maintain its quality advantage. On the other hand, the firm with the lower quality exhibit fewer incentives to innovate because reaching the competitor's high quality is a costly process that will provide zero profits if successful. As a consequence, the most likely states to be observed are those where quality differentiation is maximal. As Figure 3.6 shows, the state $(3,1)$ is reached in the long run with probability 0.20. State $(1,3)$ exhibit the same probability given the symmetry obtained in the absence of network externalities.

Second, even though the states with maximal quality differentiation are those with the higher probability in the long run, other states are also highly probable. This is a result of the firm's idiosyncratic shocks introduced in the model (i.e. probability of exogenous innovation, δ). That feature of the model implies that a firm with the highest quality level does not sustain that leading position indefinitely. As a consequence, competitors perceive a profit opportunity and compete for it. In the case of no network externalities this is a smooth process. In particular, with probability 0.14 a state (2,1) is reached. It can be shown that when this state is reached, the low quality firm increases its investment level. Thus, a symmetric state (2,2) is reached with a probability of 0.09 which may lead the former low quality firm to be the next industry leader. That is, to reach state $(1,3)$.

Figure 3.7 presents the limiting distribution when the network externalities are low. That is, it shows the case for $\omega = 0.2$. This figure highlights the role of network externalities in industry dynamics and presents three main results. These results are compared with the findings reported above for the case of no network externalities. We define a state according to the notation (i,j,f) given the relevance of the identity of the firms.

First, as in the case without network externalities, the most likely states in the long

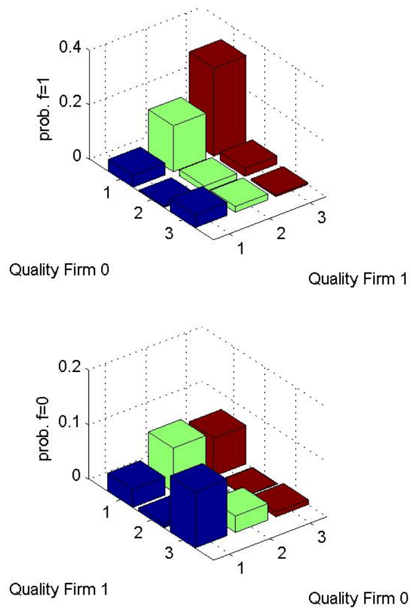

Figure 3.7: Limiting Distribution - $\omega = 0.2$ and $\delta = 0.4$

term equilibrium are those with the highest level of quality differentiation. In essence, this result follows the same argument as in the case with $\omega = 0$ and is a consequence of quality competition. However, the presence of network externalities implies that the identity of the firm plays an important role. That is, $(3,1,1) \neq (1,3,0)$. These states are reached with a probability of 0.32 and 0.10, respectively.

Second, not only the results are now asymmetric due to the presence of network externalities. The probability for a firm of being an established incumbent with the highest possible quality advantage (i.e. state $(3,1,1)$), 0.32, implies that with network externalities a dominant position is more likely to be sustained. This is not a surprising result given the advantage provided by the installed base and the effect on consumer expectations.[22] However, the model also suggests that this predominance of an established incumbent is not a permanent phenomenon and this lead us to our third result.

Third, even though the industry tend to be dominated by an established incumbent,

[22]Recall that in making consumption decisions, consumers expect a higher surplus from the firm with an installed base in the case of equal quality levels.

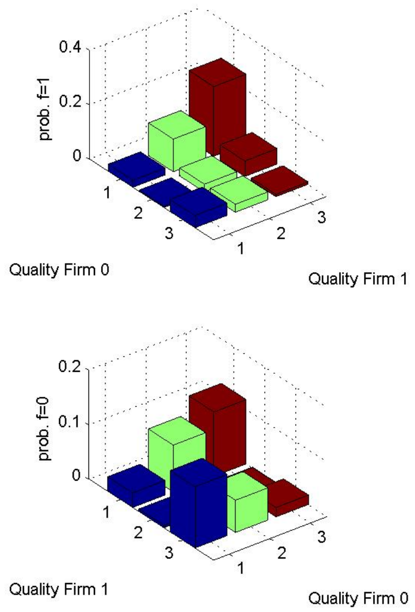

Figure 3.8: Limiting Distribution - $\omega = 0.8$ and $\delta = 0.4$

this is not a permanent result. This represents a contrast with the current literature on the evolution of network industries. Moreover, the process of a new leader overtaking the market is not as smooth as the case without network externalities.

Finally, we can briefly consider the same analysis just presented, but taking into account a more important role of the network externalities parameter. Figure 3.8 shows the limiting distribution for $\omega = 0.8$

The qualitative results for the case of $\omega = 0.8$ are similar to those presented for the case of $\omega = 0.2$. However, if the importance of the network externalities is increased, the possibility of a new leader in the industry overtaking the market if more likely. As presented before, network externalities provide an incentive to firms to increment their investment and attempt to capture the market and become an established incumbent with the benefits of an installed base. This incentive has an impact on the level of investment of a firm with a low quality level. This incentive is not present in the case without network externalities, and even, when the parameter that measures the extent of the network effects is low.

	$\omega = 0.0$	$\omega = 0.2$	$\omega = 0.8$
$\delta = 0.1$			
$\mathrm{E}(\pi(i,j,f))$	1.38	1.39	1.48
$\mathrm{E}(x(i,j,f))$	0.28	0.24	0.30
$\mathrm{E}(V(i,j,f))$	10.97	8.42	9.57
$\delta = 0.4$			
$\mathrm{E}(\pi(i,j,f))$	2.05	1.98	2.32
$\mathrm{E}(x(i,j,f))$	1.00	0.71	0.81
$\mathrm{E}(V(i,j,f))$	10.50	9.22	11.84
$\delta = 0.7$			
$\mathrm{E}(\pi(i,j,f))$	0.88	1.12	1.94
$\mathrm{E}(x(i,j,f))$	0.61	0.52	0.86
$\mathrm{E}(V(i,j,f))$	1.33	3.32	7.04

Table 3.1: Industry Performance - Market Outcome

In addition, is important to see what is the impact of the quantitative difference that are obtained given the variation of the parameters of interest. We show this analysis in the following subsection.

3.3.3 Industry Performance

Having computed the limiting distribution of the industry evolution, we can using it to calculate the steady state expected per-period profits ($\pi(i,j,f)$), the levels of investment ($x(i,j,f)$) and the overall discount profits observed in the industry ($V(i,j,f)$). Table 3.1 presents some of these results, considering different values of the parameter of interest.

In particular, the expected per-period profits are non-monotonic in the behavior of the probability of exogenous innovation δ. That is, low and high values of δ are associated with a low level of profits. On the contrary, moderate levels of the probability of exogenous innovation tend to boost profits. This result suggest that for too low pressure outside the two firms, the cost associated with innovating in R&D are not compensated by the increase in expected profits. The reason is that under low external competition, a dominant position is achieved with less intensity in R&D. Analogously, under very high external competition, it is too costly to maintain a dominant position and therefore the most profitable states are less likely to be reached.

The expected investment level shows a similar pattern non-monotone as the one observed for the per-period profits with respect to the probability δ of exogenous innovation (i.e. inverted U-shaped behavior). Under too low or too high external competition the benefits associated to invest in R&D do not compensate the cost of it (see discussion below). However, as the last column of Table 3.1 shows, this situation can be reversed for very high network effects. This result may appear counterintuitive. As stated before, high levels of δ imply that the quality loses some of its value in a relatively frequent manner. Therefore, a firm cannot maintain its advantage indefinitely, there is less possibility of preempt a competitor and incentives to innovate should decline. For high network effects, preemption becomes more feasible and this may increase the incentives to innovate. We extend this result in the Discussion section.

3.3.4 Social Planner

One of the main objectives of this chapter is to analyze the social efficiency of the private incentives to innovate. In order to do this, we solve for the social planner problem. This is done by considering the case of a monopolist in charge of the two technologies (i.e. network goods) and that prices equal to marginal cost (i.e. zero and therefore maximizing consumer surplus which is equal to social surplus in our homogeneous consumer framework presented in equations (3.1) and (3.2)).

The main result obtained by analyzing the problem of the social planner is that there is too much R&D in the industry. The main implication of this result is that there is too much introduction of improved goods in the market. In particular, Figure 3.9 shows the socially optimal level of investments for $\delta = 0.4$.

Given that the social planner internalizes the costs associated with the quality improvements, it tends to concentrate investment in the firm that exhibits a quality advantage. This result implies that a technology that exhibits a better quality tend to stay as the preferred technology because it maximizes the network benefits enjoyed

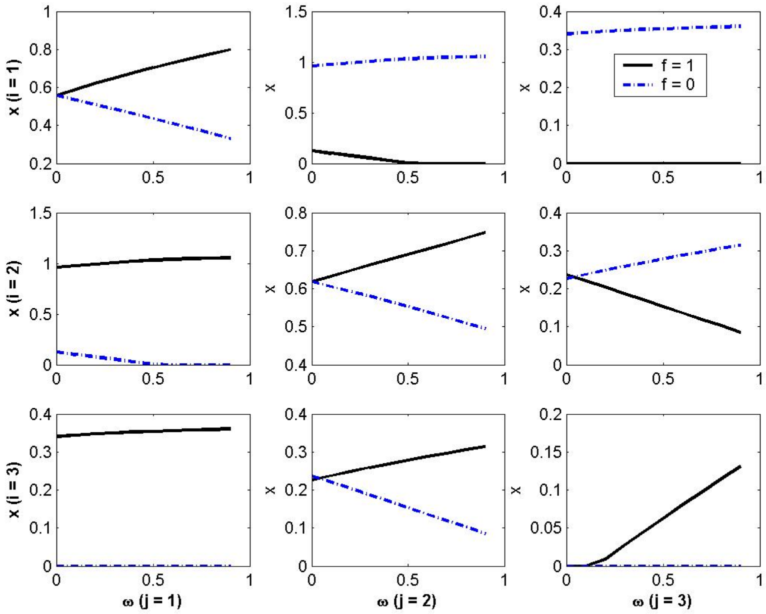

Figure 3.9: Social Planner - Investment Levels ($\delta = 0.4$)

by the population. As a consequence, this result also shows that the market outcome induces too much introduction of new incompatible technologies.

Figure 3.10 shows the extent of the inefficiency exhibited by the firm with the installed base, while Figure 3.11 presents the case of the firm that lacks the installed base. These figures explicitly show that in the presence of network externalities, firms competition tend to generate an over-investment behavior in comparison with the social optimum. Moreover, the inefficiency is greater, the greater the network effects.

Table 3.2 presents some results for the social planner's problem that can be compared with the results presented in Table 3.1. In particular, it presents two important results. First, high levels of δ reduce the expected social surplus and also reduce the expected investment levels. And second, it states that with high competition outside the industry (high δ), the extent of network externalities is critical in determining the size of the inefficiency associated with the investment levels (see discussion below).

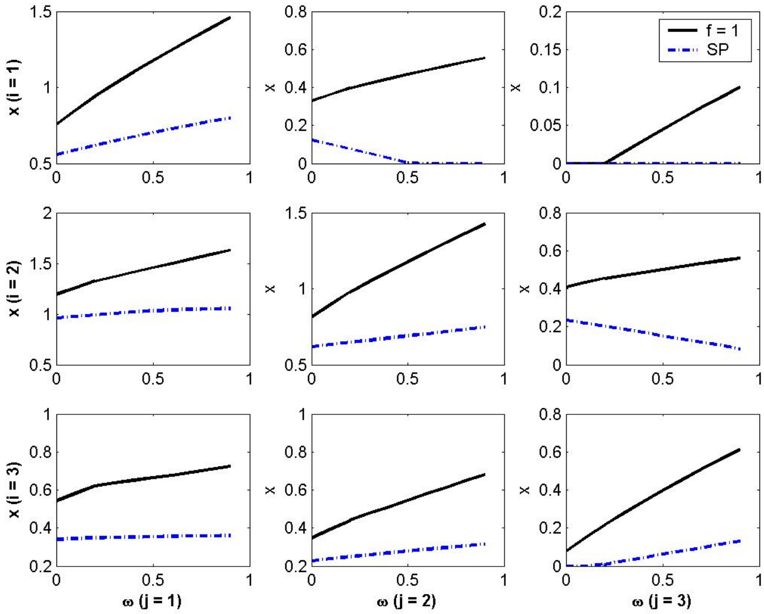

Figure 3.10: Efficiency - Investment Levels for $f = 1$ ($\delta = 0.4$)

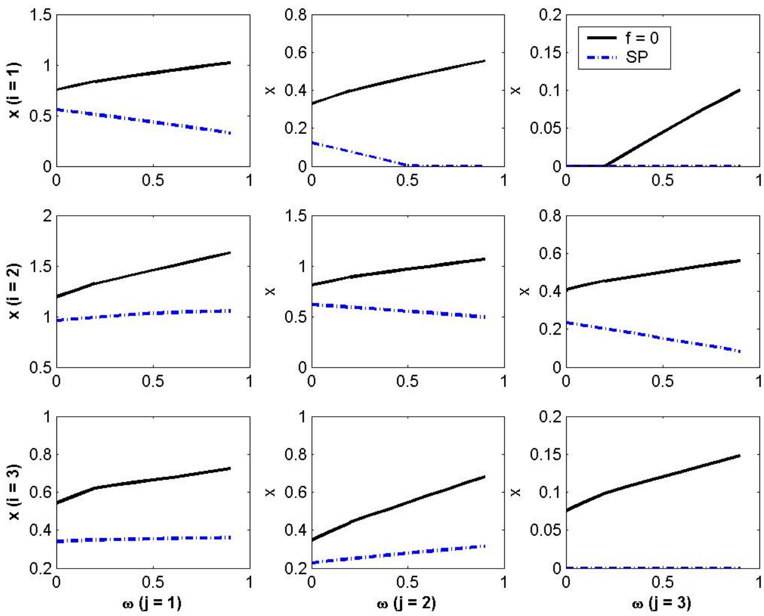

Figure 3.11: Efficiency - Investment Levels for $f = 0$ ($\delta = 0.4$)

	$\omega = 0.0$	$\omega = 0.2$	$\omega = 0.8$
$\delta = 0.4$			
$\mathrm{E}(\pi(i, j, f))$	4.44	3.01	5.20
$\mathrm{E}(x(i, j, f))$	0.76	0.55	0.63
Inefficiency on x	0.31	0.25	0.38
$\delta = 0.7$			
$\mathrm{E}(\pi(i, j, f))$	1.66	1.75	3.76
$\mathrm{E}(x(i, j, f))$	0.53	0.38	0.46
Inefficiency on x	0.08	0.13	0.43

Table 3.2: Industry Performance - Social Planner

3.4 Discussion

The previous section presented the general results of our model. In this section we highlight the results that provide the most interesting comparison with the economic literature and discuss their relevance. We focus the discussion around three main results. First, in the presence of high outside competition, the model predicts a high expected level of investment when the extent of network externalities is high. Second, for any parameter configuration, the expected steady state investment levels are socially inefficient in the sense that is above the value that maximizes social surplus. And third, with high competition outside the industry, the extent of network externalities are critical on determining the size of the inefficiency associated with the investment levels.

The first result shows that in the presence of high network effects (ω), the expected level of investment is increasing in the level of competition (δ). In order to show the importance of this result, we need some insights from the literature on innovation and its approach on the interaction of the level of competition and market innovation.

Specifically, the Schumpeterian approach to market innovation states that in the event of an increase in competition, firms tend to reduce their innovation levels because higher competition dissipates some of the rents associated with higher market power (i.e. lower competition). This has been termed the "Schumpeterian effect". However, it has been empirically shown that in some cases the relation is positive.[23]

This case of direct relation between the level of competition and the incentives to innovate is partially consistent with the Schumpeterian view. This is so, because in the presence of a positive relation between the level of competition and market innovation, the expected rents from innovating are reduced by the presence of higher competition as the Schumpeterian view sustain. However, higher competition may imply higher innovation if the rents from *not* innovating are much lower (i.e. even though under higher competition innovation is less profitable, is better than not innovating). This has been termed the "escape effect".

In general terms, the two effects have been made compatible by Aghion et al. (1997) and Aghion et al. (2001). In particular, the level of innovation behaves as an inverted U-shape function in relation to the level of competition.[24] That is, for low levels of competition, the investment level tend to increase as competition become fiercer (i.e. escape effect) and, eventually, starts declining in the presence of high competition (i.e. Schumpeterian effect). As shown in the previous section, this is exactly the behavior of the level of innovation without network externalities (see Figure 3.1 and Table 3.1).

Surprisingly, as the first result considered in this discussion states, for high network effects (ω), high level of competition (δ) implies *higher* investment levels (as shown in Table 3.1). In other words, the escape effect dominates the Schumpeterian effect and the relation between innovation incentives and the level of competition is not an U-shaped function but a monotone increasing function. This result says that the expectation of exhibiting future installed bases is so strong, that even considering the case of being a technological laggard, higher innovation are, on expectation, worth pursuing. In addition, this result rationalizes the observed high technological competition in network industries.

The second result is in line with the current literature on technological innovation in network industries. The result states that for any parameter configuration, the expected steady state investment levels are socially inefficient in the sense that they

[23] See Geroski (1995), Nickell (1996) and Blundell, Griffith and Van Reenen (1999).

[24] This theoretical finding is in line with the empirical results of Scherer (1967), Levin et al. (1985) and is specifically tested in Aghion et al. (2005).

are above the value that maximizes social surplus. In particular, although the presence of installed bases tend to suggest that inefficient technologies might capture the market for a (socially too) long period of time, our model suggests the opposite. That is, there is too much investment in comparison with the level that would maximize social surplus and, in consequence, there is too much quality improvement in the market.

Moreover, Katz and Shapiro (1992, 1994) also argue in favor of too much innovation in network markets and state that in contrast to the common presumption that these markets tend to be biased in favor of existing product, there is actually a tendency to rush on new incompatible technologies. In that sense, our results are consistent with the current literature on innovation in network markets. However, our results are derived from a fully dynamic setup with endogenous and stochastic R&D incentives.

The third result states that with high competition outside the industry, the extent of network externalities is critical in determining the size of the inefficiency associated with the investment levels. This result shows that in the presence of high outside competition (high δ), the inefficiency associated with the investment level is minimal when network externalities are not present. As network effects become more important, the inefficiency is increased monotonically (see Table 3.2).

This result is important because it permits to see a clear impact of the role of network externalities in determining innovation incentives and the associated social efficiency. Moreover, this result implies that in order to pursue a correct public policy, it is necessary to know the extent of network externalities. Otherwise, a measure that attempts to correct an inefficiency in the levels of innovation, and therefore in the process of adoption of new technologies, may imply a higher costs that the potential benefits it was intended to provide.

3.5 Conclusions

In this chapter, we proposed a dynamic model of quality competition in the presence of network externalities that adapts the Markov-perfect equilibrium framework presented in Ericson and Pakes (1995). Incentives to invest in R&D are derived endogenously.

The focus of this chapter was twofold. First, to see the impact of network externalities in the incentives to innovate in a fully dynamic framework. And second, the analysis of the social efficiency of the R&D levels predicted by the market outcome. The robustness of the presented results with respect to the assumed functional forms is the objective of current work.

We showed four main results. First, the presence of network externalities generates important incentives to invest in R&D in order to innovate. This investment levels are higher than the levels that would be observed without network externalities. This result has three important implications: i) with a positive probability, the traditional result of "monopolization" in one network technology can be overcome, resembling the industry evolution of temporary monopolists; ii) the threat of losing the market induces the established firm to follow R&D projects in order to reduce the probability of being overtaken by the challenger; and iii) the challenger firm has enough incentives to try to overtake the market. These results are in clear contrast with the current literature that predicts that successful firms remain as incumbents forever.

Second, for high network effects, a high level of outside competition implies higher investment levels. This result implies that the relation between innovation incentives and the level of competition is not an U-shaped function, as traditional innovation theory for non-network industries suggests, but is a monotone increasing function. This result says that the expectation of exhibiting future installed bases is so strong, that even considering the case of being a technological laggard, higher investment levels are, on expectation, worth pursuing. In addition, this result rationalizes the observed high technological competition in network industries.

Third, we analyze the incentives to innovate for both firms, we compare it to the social optimum and investigate the role of the network externalities. We find that the market tends to over-invest in R&D in comparison with the level that maximizes social surplus. This implies that introduction of new incompatible technologies occurs too often in equilibrium.

And fourth, with high competition outside the industry, the extent of network externalities is critical in determining the size of the inefficiency associated with the investment levels. This result shows that in the presence of high outside R&D competition, the inefficiency associated with the investment level is minimal when network externalities are not present. As network effects become more important, the inefficiency is increased monotonically. This result permits to see a clear impact of the role of network externalities in determining innovation incentives and the associated social efficiency.

We recognize several areas of further research in the area of R&D incentives in the presence of network externalities. A deeper analysis of the different ways about how consumers form expectations (or coordinate) may provide new insights on the interplay between R&D incentives in network industries. That is the subject of current research. In addition, the analysis of compatibility decisions must also be considered given its obvious relevance in these industries but for the time being beyond the scope of the present chapter.

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Eidesstattliche Versicherung

Ich versichere hiermit eidesstattlich, dass ich die vorliegende Arbeit selbständig und ohne fremde Hilfe verfasst habe. Die aus fremden Quellen direkt oder indirekt übernommenen Gedanken sowie mir gegebene Anregungen sind als solche kenntlich gemacht. Die Arbeit wurde bisher keiner anderen Prüfungsbehörde vorgelegt und auch noch nicht veröffentlicht.

München, den 4. März 2005

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