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ESSAYS ON FIRM R&D STRATEGIES AND MARKET DESIGN

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

SUMMARY

This thesis includes three essays on firms' R&D strategies and standard choices under different market structures. The first two chapters contribute to the literature on firm innovation. The third chapter contributes to the literature on standard adoption. Each chapter can be considered independently of the rest.

Chapter 1 empirically investigates how firms choose their R&D strategies depending on both internal firm characteristics and external market parameters, focusing on the effect of intellectual property protection and competitive pressure. Three R&D strategies are considered: to abstain from innovation, to imitate or to innovate. The analysis draws upon the data for German firms from manufacturing and services sectors covering the year 2005. The results show that the efficiency of patent protection positively affects innovation and imitation for any level of competition except the case of the markets with few competitors. In markets with few competitors better patent protection raises firms' incentives to innovate (to introduce market novelties) and decreases firms' incentives to imitate (to introduce improvements into already existing products). Finally, in markets where firms have almost monopoly power an increase in patent protection enhances the introduction of improved products (i.e. imitation) more than the introduction of new products (i.e. innovation). A decrease in competitive pressure from many to few competitors positively affects the propensity of firms to improve already existing products, and to introduce market novelties. This effect varies with patent protection efficiency. For low levels of patent protection both innovation and imitation are enhanced, while for high levels of patent protection imitation is reduced and innovation is enhanced. A further decrease in competitive pressure from few competitors to no competitors diminishes innovation and favours imitation. The analysis of firm R&D strategy choices at the industry level provides support to conclusions obtained at the firm level.

In order to provide a theoretical rationale for the observed evidence on firms R&D strategy choice Chapter 2 assumes a firm's R&D strategy to be endogenous and allows it to depend on both internal firms' characteristics and external factors. Firms choose between two strategies, either they engage

in R&D or abstain from own R&D and imitate the outcomes of innovators. This yields three types of equilibria in which either all firms innovate, some firms innovate and others imitate, or no firm innovates. Firms' equilibrium strategies crucially depend on external factors. We find that the efficiency of intellectual property rights protection positively affects firms' incentives to engage in R&D, while excessive competitive pressure has a negative effect. In addition, smaller firms are found to be more likely to become imitators when the product is homogeneous and the level of spillovers is high. Regarding social welfare our results indicate that strengthening intellectual property protection can have an ambiguous effect. In markets characterized by a high rate of innovation a reduction of intellectual property rights protection can discourage innovative performance substantially. However, a reduction of patent protection can also increase social welfare because it may induce imitation. This indicates that policy issues such as the optimal length and breadth of patent protection cannot be resolved without taking into account specific market and firm characteristics.

Chapter 3 derives a model for markets with system goods and two technological standards. An established standard incurs lower unit production costs but causes a negative externality. In the absence of policy intervention, with an established technological standard, firms have no incentives to adopt a superior standard. Therefore, the present paper compares the effect of direct and indirect cost-reducing subsidies in markets with system goods in the presence of externalities. The conditions for optimal subsidies are indicated depending on the cost difference between standards, the impact of the externality and the presence of consumers' "commitment" to a determined technology. If consumers' purchasing decision is made before the prices of one of the components of the system good are known, policy intervention is desirable only when the impact of the externality is not lower than the cost difference between standards. Then, if the impact of the externality is relatively similar to the cost difference between standards, it is optimal to give a direct subsidy only to the first technology adopter to provide incentives for the transition to the superior standard. Furthermore, the higher the externality becomes, the more technology adopters must be targeted with subsidies. This means that in case of direct subsidies, both technology adopters should be given a direct cost-reducing subsidy per unit of production using the superior standard. In case of indirect subsidies, the necessary amount of cost-reducing subsidies should be given to the producers of the complementary component per volume of production using the superior standard. The comparison between direct and indirect subsidies suggests that when the cost difference between technological standards is high and the externality is low or intermediate, direct subsidies are socially preferable. When the externality cost is high and the cost difference is low, direct and indirect subsidies perform equally. However, because the optimal indirect subsidy is higher than the direct subsidy, the direct subsidy leads to higher social welfare. If consumers' purchasing decision is made after the prices of all components of the system good are known the effects of indirect and direct subsidies' are equal. In this case, if the production cost difference is low the first adopter might have natural incentives to adopt the superior technology. This means that the adoption of the superior technology implies a lower cost for society. If the production cost difference is high, the adoption requires direct or indirect subsidies. Moreover, the subsidy to the second adopter is higher than the subsidy to the first adopter. Finally, compatibility between components based on different technological standards enhances an advantage of indirect subsidies when both the externality cost and the cost difference between an established and a superior technological standard are high.

CHAPTER I

THE EFFECT OF COMPETITION AND INTELLECTUAL PROPERTY PROTECTION ON R&D STRATEGY CHOICES OF GERMAN FIRMS: AN ANALYSIS AT A FIRM AND AN INDUSTRY LEVEL

1.1 Introduction

In recent economic literature the impact of market structure on firms' innovativeness has received much attention. In particular, there are two major debates regarding the impact of intellectual property rights (IPR) protection and competitive pressure. The first debate discusses the impact of IPR protection on firm innovative performance. In line with it, two confronting views are present. According to the first view, IPR protection is a necessary mechanism that provides incentives for firms to engage in R&D and encourages technology transfer between firms. Therefore, strong protection of intellectual property rights would be the optimal R&D policy (Arora and Gambardella, 1994; Gallini and Scotchmer, 2002; Gans and Stern, 2003; Gans et al., 2008; Boldrin and Levine, 2008). However, this view has recently been challenged by Aghion et al. (2001), Bessen and Maskin (2009) and Zhou (2009) who show that stronger imitation fosters innovative efforts by incumbent firms and patent protection can block the future development of technologies. The second debate concerns the effect of competitive pressure on firm innovation. Some studies suggest a monotonic (positive or negative) relationship between competitive pressure and firm R&D expenditures (Henderson and Cockburn, 1996; Dasgupta & Stiglitz, 1980; Geroski, 1990; Blundell et al., 1999), while others propose a non-monotonic inverted-U (Aghion et al., 2005) or U-relationship (Tishler and Milstein, 2009). Noteworthy, most of the above mentioned studies use total R&D expenditures as a proxy for the entire innovation process and assume that firms' innovation strategies are homogeneous, i.e., all firms invest in R&D and innovate. However, empirical evidence suggests that most markets are characterized by heterogeneous

R&D activities within as well as across markets. This heterogeneity arises as the result of firms' decisions to engage in R&D or to abstain from own R&D and imitate the outcomes of innovators. Taking firms' R&D strategy choice into consideration indicates that any policy intervention, concretely, IPR protection and competition policy, might not only affect the amount of firm R&D expenditures but also the R&D strategies adopted by firms.

The present study is novel in three ways. First, it analyzes firms' R&D strategy choice distinguishing between innovative and imitative strategy. Therefore, it employs a discrete choice model (stereotype logistic regression). Second, we include explanatory variables that were not considered jointly in previous studies. These are internal firm characteristics and external market parameters, concretely, the intensity of IPR protection, competitive pressure measured by the number of competitors and the degree of product differentiation. To the best of my knowledge, until now no studies have investigated how both IPR protection and competitive pressure affect firms' R&D strategy choice. In addition, no attention has been paid to potentially existing complementarities in the effects of IPR protection level and competitive pressure on firms' choice to innovate and to imitate. Third, it extends the analysis of firms' R&D strategy choice at the industry level, providing robustness check to the results obtained at the firm level with a count data model (negative binomial regression).

In the empirical model derived in this chapter, the dependent variable represents a firm's R&D strategy choice between the following alternatives: no innovation, imitation and innovation. The explanatory variables are internal factors (firm size, human capital, capital and export intensity, organizational structure and the geographical scope of the market) and external factors (the efficiency of IPR protection by patents and trademarks, competitive pressure measured by the number of main competitors, and product substitutability). The results suggest that firms' R&D strategy choices are tightly related to internal firm characteristics and external market factors. Firm size and human capital quality positively affect a firm's propensity to innovation and imitation, although the latter effect is higher in magnitude than the former. Geographical market size strongly positively affects a firm's propensity to improve existing products (imitation) and to introduce market novelties (innovation).

Regarding external factors, the results show that the efficiency of patent protection positively affects the propensity of firms to imitate or to innovate. A decrease in competitive pressure from many to few competitors positively affects the propensity of firms to improve already existing products, and to introduce market novelties. This effect varies with patent protection efficiency. When patent protection is low, both innovation and imitation are enhanced, while when patent protection is high, imitation is reduced and innovation is enhanced. A further decrease in competitive pressure from few competitors to no competitors disseminates innovation and favours imitation.

The findings of this study suggest to look beyond overall R&D expenditures when analyzing innovative performance in industries. This is because firms choose R&D strategies that in turn affect overall innovative performance of industries. In addition, the present analysis derives a link between IPR protection policy and competition policy. The two policies should be tightly coordinated because IPR protection and competitive pressure jointly affect firms' R&D strategy choice. In particular, better patent protection or longer patent duration positively affect innovation and imitation for any level of competition except the case of the markets with few competitors. In markets with few competitors better patent protection raises firms' incentives to innovate and decreases firms' incentives to imitate. Finally, in markets where firms have almost monopoly power an increase in patent protection increases the introduction of improved products (imitation) more than the introduction of new products (innovation).

The rest of the paper is arranged as follows. Section 2 presents a literature review. Section 3 describes the data and variables for the empirical analysis. The econometric model is presented in Section 4. Section 5 discusses the results. Finally, Section 6 derives some policy implications and concludes.

1.2 Literature review

This paper is related to a large literature on the relationship between market structure and innovation strategy. Specifically, it is related to two strands. The first strand analyzes how firms' R&D investments are affected by market competition. Pioneer works in this field are those of Schumpeter (1934 and 1942) who argues that, on the one hand, market pressure may foster firms' innovation, but, on the other hand, it may decrease firms' R&D investments because monopoly power of larger firms acts as a major accelerator of technological progress. Actually, there is still no accordance on this Schumpeterian debate in theoretical and empirical studies. For example, some authors argue that more intensive market competition decreases a firm's incentives for innovation because when advantages from innovation are temporary, only sufficient market power guarantees that firms invest in R&D (Arrow, 1962; Futia, 1980; Gilbert and Newbery, 1982; Reinganum, 1983; or Zhou, 2009). This argument is supported by empirical studies, which find that market concentration increases the pace of innovative change. For instance, Henderson and Cockburn (1996) show that large firms in the US pharmaceutical industry perform R&D more efficiently, as they can enjoy scale and scope economies. Using patent data of UK manufacturing firms, Cefis (2003) finds that, due to innovative effort, the contribution of large firms to aggregated industrial performance is above the industry mean. On the other hand, market concentration is also argued to have a dampening effect on innovation because more intensive competition acts as an important incentive for firms to innovate (Dasgupta & Stiglitz, 1980). Again, these theoretical arguments are supported by empirical evidence (Geroski, 1990; Blundell et al., 1999).

These contradictory results led to the hypothesis that the effect of market competition on firms' innovative efforts is non-monotonic. For example, Boone (2000) finds that when competition is weak, the incentives of less efficient firms to innovate increase. However, when competition becomes more intense, the incentives of efficient firms to innovate grow. Aghion et al. (2005) suggest the existence of an inverted-U relationship. Both, a low or high level of competition provide low incentives to innovate while a medium level of competition fosters innovation of firms operating on a similar technological level ("neck-and-neck firms"). On the contrary, Tishler and Milstein (2009) find that R&D investments decrease with competitive pressure. However, at a certain level of competition firms engage in "R&D wars" and spend excessively on R&D.

The above mentioned literature assumes that firms' innovation behavior is homogeneous, that is, that all firms innovate by spending on R&D. However, empirical evidence suggests that most markets are characterized by an elevated heterogeneity of R&D activities. For instance, using data of Italian firms, Cefis and Orsenigo (2000) and Cefis (2003) find that in most markets there is a core of firms that are persistent innovators while other firms either are occasional innovators or imitators. Czarnitzki et al. (2008) find that, depending on a firm's role in the market, competitive pressure might have a different effect on innovative effort. So, while entry pressure decreases the average investment per firm, it increases innovative effort of market leaders. Vives (2008) distinguishes between process R&D aimed at reducing production costs and product innovation aimed at new product introduction. He considers the degree of product substitutability and the number of competitors as indicators of competitive pressure. The main finding for process innovation is that an increase in the number of competitors decreases cost-reduction expenditures, while an increase in product substitutability increases it. For product innovation the results are ambiguous.

The second strand of the literature to which this paper is related are studies that distinguish between firms that innovate and those that imitate the outcomes of innovators' activity. Theoretical studies have analyzed the effect of the possibility of imitation on innovative incentives in two frameworks, economic growth models (Grossman & Helpman, 1991; Aghion & Howitt, 1992) and oligopolistic competition models (Zhou, 2009). In both cases, the imitation rate is assumed to be exogenously determined. In some studies, imitation is shown to foster the innovation activity of technological leaders. This finding challenges the common view that patent protection should be strengthened. In fact, strong IPR protection may slow down the development of countries and decrease world welfare and consumer surplus (Helpman, 1993; Bessen & Maskin 2009; Che et al., 2009; Fershtman & Markovich, 2010). Additionally, Braguinsky et al. (2007) find that the relationship between innovation and imitation itself depends on other factors such as the maturity of an industry. When the industry is young and small, innovators do not have incentives to prevent imitation. But when the industry expands, innovative effort decreases because of imitation pressure. In other studies, IPR protection is shown to be a necessary mechanism that provides incentives for firms to engage in R&D and encourages technology transfer between firms. Therefore, Gans and Stern (2003), Gans et al. (2008), Boldrin and Levine (2008) suggest strong protection of intellectual property rights as the optimal R&D policy.

Most of this literature assumes that innovators and imitators are exogenously given. Exceptions in the theoretical literature are Segestrom (1991) and Amir and Wooders (2000). Applying an economic growth model, Segestrom (1991) allows firms to participate in both innovative and imitative R&D races. In the steady-state, firms' equilibrium R&D strategies depend on the distribution of previous R&D outcomes and the relative price of imitation. Firms are found to benefit more from imitation in industries with a single leader, while in industries with several leaders innovation is a more profitable strategy. In a standard oligopoly framework, Amir and Wooders (2000) show that, in equilibrium, firms choose their R&D strategies asymmetrically. This gives rise to an innovator/imitator configuration in the market. Regarding the empirical literature, the determinants of firms' R&D strategy choices have been studied by a small number of authors. Using US marketing data, Robinson and Min (2002) find that innovators face higher survival risks associated with technological uncertainties. On the other hand, Zhou (2006) finds that in the presence of demand uncertainty or with more competitive pressure firms obtain higher benefits from being pioneers in innovation. Shankar et al. (1998) analyze data on sales and advertising of 13 brands of ethical drugs in the US. They show that imitators with a slightly differentiated product can grow faster than initial innovators. Therefore, in the presence of rapidly changing technologies, in the long run, imitators obtain higher benefits than innovators because the innovator's initial profits are rapidly discouraged.

The present paper builds upon Link and Neufeld (1986) who distinguish between, innovation, imitation and non-innovation. Using cross-sectional data they analyze firms' strategy choice as a function of firm size, market share, and industry concentration. The present paper is similar to their study in that it explores how market design affects firms' choice between innovation and imitation. However, we improve competitive pressure measures by considering various indicators such as the number of competitors and product differentiation and take into account IPR protection, which is important for firms' incentives for product innovation. We explore how competition measures affect firms' R&D strategy choice given different levels of IPR protection efficiency in the industry.

Despite the extensive existing research on firm innovativeness, empirical studies have the following drawbacks. During the last decades they discussed the determinants of R&D activity mainly based on internal firm characteristics such as firm size, appropriability of the outcomes of innovation, access to international markets, cooperation with customers, suppliers and others (Patel and Pavitt, 1992; Crépon et al., 1998; Loof and Heshmati, 2002; Veugelers and Cassiman, 2005). Less attention has been paid to external factors. This certainly is due to the problems that its measurement rises. For example, the intensity of market competition has been proxied with concentration measures, such as concentration ratios or the Hirshman-Herfinadahl index, based on industry data (Geroski, 1990; Blundel et al., 1999; Aghion et al., 2005). The problem with this approach is that the market in which firms compete can hardly be identified by the industrial sector. So, firms within one sector might not compete at all if their products meet different consumer needs. Another example is the measurement of spillovers. The average spillover level has been measured with industry data as an average of firm R&D expenditures in the industry (Bloom et al., 2007; Czarnitzki and Kraft, 2007). However, firms can protect the outcomes of their R&D activity by using legal protection mechanisms as well as by secrecy. So, this indicator might wrongly reflect the spillover level in the industry or in the market.

The present empirical analysis contributes to the literature by including firm internal characteristics as well as external market parameters (competitive pressure, spillover level, and product substitutability) in the analysis of a firms' R&D strategy choice. This is important, because the innovation strategy of a firm must be considered in the context of its global market strategy as it serves to maintain and improve the firm's market position. Therefore, when managers decide to launch an R&D project, they consider both internal firm characteristics and external factors such as rivals' strategies, competitive pressure, knowledge specificity, intellectual property protection, availability of funding, public support, etc. A variation in one of these external factors might critically affect the firm's resources and capabilities and thereby the firm's innovation strategy.

The common problem with the measurement of these variables is that market characteristics such as the firm's market position or the level of knowledge protection are not directly observable. The Mannheim Innovation Panel (MIP), a survey used in this study, allows to improve the measures of external factors. This is because firms provide information about these factors according to their own perceptions of market characteristics, which definitely determine their R&D strategies.

1.3 Data

To investigate the determinants of firms' R&D strategy choices, the data from the MIP innovation survey is applied. This survey is conducted by the Centre for European Economic Research (ZEW) on a yearly basis. It covers a representative sample of German firms in manufacturing and service sectors during the period 1995-2007. The data includes information regarding the introduction of new products, services and innovation processes within firms. The database has cross-sectional structure such that survey questions differ across waves. Because only the 2005 innovation survey, which is the 13th wave of the MIP, provides necessary data it is used for the purposes of this study. In this survey, firms are asked about both internal and external factors that affect their commercialization and innovation decisions during the period 2002-2004. Enterprises with 5 or more employees are covered. The drawing probabilities are disproportional with higher drawing quotas applied for large enterprises, enterprises from Eastern Germany and from sectors with a high variation in labour productivity. For the analysis at the industry level, additionally, the data provided by the Monopolkomission (Germany) are used.

The dependent variable of the analysis at the firm level represents a firm's R&D strategy choice (*str*). *str* is a categorical variable that indicates if, between 2002 and 2004, a firm did not conduct innovations (0), introduced a product that is new for the firm but known in the market (1) or introduced a product that is new for the market (2). The questions in the survey that allow to distinguish between innovators and imitators refer only to product innovations, therefore, implications derived in the present study are applied, mainly, to product innovation. In addition, firms that haven't introduce any new product because they aborted or did not finish innovation during the period of observation are excluded from the sample. This allows to exclude from consideration those factors that impede innovation success despite a firm's willingness to innovate.

As it is common in the economic literature, we interpret the introduction of a product that is new for the market as innovation while the introduction of a product that is new for the firm (but not for the market) as imitation. This interpretation is supported by Link and Neufeld (1986), who surveyed 76 R&D active US manufacturing companies. The vice presidents were asked whether their firm's overall R&D strategy was innovative or imitative and whether this classification is meaningful. All of them reported that although their firms operated in several lines of business, one dominant strategy characterized the overall R&D effort. However, the dependent variable of their analysis has an important drawback. It is based on the subjective vision of vice presidents of the companies and has retrospective nature. Therefore, in the regression analysis with contemporaneous market characteristics the problem of endogeneity arises. On the contrary, the dependent variable of the present paper allows to identify the outcome of the strategy chosen by a firm. Thereby, the direct endogeneity due to the simultaneity in observations is avoided. The dependent variable employed in this study can also be interpreted as the degree of innovation. Then, category 1 refers to incremental innovation (the improvement of already existing products) and category 2 refers to more radical innovation (the introduction of a new product, which did not exist in the market before).

The representative sample of German firms used for this study shows that the rate of innovating and imitating firms varies across industries. In Table 1 we display the rate of innovating firms for manufacturing and services sectors in the year 2005. The highest rate of non-innovating firms can be observed in manufacturing sectors such as agriculture, mining, wood / paper, metals and furniture, and many of the services sectors. On the other hand, in sectors such as chemicals, medical instruments and electrical equipment we find that most firms are innovators. Thus, we observe that firms' R&D strategies vary across industries and markets. Hereafter, to study firms' R&D strategy choices, we include two categories of independent variables into our empirical model: variables that measure internal and external factors. As commonly used in firm-level studies, our internal factors are: firm size ($size02$) and its square ($size02\_2$), the quality of human capital ($hc03$), capital intensity ($capint$), export intensity ($expint$), a dummy for firms' group membership ($group$), geographical market size to which a firm accesses (geo), and, specific to our data, firm location in the territory of former Eastern Germany (ost).[1]

Most studies on firm innovation control for firm size, measured by the number of employees or turnover, as larger firms are supposed to be more efficient in the conduct of innovation (Henderson and Cockburn, 1996; Shefer and Frenkel, 2005). In the present study $size02$ and $size02\_2$ measure the number of employees and its squared value to control for a non-monotonic effect of firm size. Regarding $size02$, a positive effect is expected. However, the magnitude of the effect is expected to decreases for very large firms, resulting in a negative effect of $size02\_2$. Regarding the $group$ dummy, previous studies suggest that firms, which belong to a group, have more incentives and resources for innovation. geo is used as a proxy for the firm's market size. We create 4 dummies to distinguish between geographical scope of markets that firms access: local or regional markets, the German (i.e. nation-wide) market, the market of EU member, EU candidate and EFTA member countries and the world market. Following previous studies, positive effects of $group$ and geo on a firm's propensity to engage in R&D are expected.

Apart from the traditional internal factors mentioned above, the literature stresses the importance of the so called "absorptive capacity" for firms' innovation activity. According to Cohen and Levinthal (1989), this term stands for a firm's ability to identify, assimilate and apply new knowledge given the firm's experience, human capital skills, and organizational procedures' flexibility and relevance. Firms that have more advanced human capital are expected to dispose of more capability for R&D. Therefore, $hc03$ is considered among firm characteristics as a measure of human capital. There is a number of

[1] Numbers in the variable definitions indicate the year of measurement.

ways to measure a firm's human capital (see Schmidt, 2005). Given the cross-sectional structure of our data, $hc03$ is measured as a firm's proportion of all employees with a university degree or other higher education qualification in 2003. As firm performance depends on its employees skills, the general level of education, experience and training of employees, this seems to be a good proxy for a firm's human capital quality. Finally, we use the dummy variable ost to control whether a firm is located in former Eastern Germany. Historically, firms that belong to the western and the eastern part of Germany were affected by different policies (subsidies, taxes, institutions). As a consequence, there might exist a systematic difference in the innovative performance between firms in these regions.

Regarding the external factors, our variables are: intellectual property rights protection by patents (pat) and trademarks (tm), competitive pressure (com), and the degree of product differentiation (dif). The MIP survey is based on firms' perceptions regarding their external environment. Because manager's decisions are based on their subjective perceptions of external factors this allows to assess better the determinants of firms' R&D strategy choices. The external factors pat, tm, dif are represented by categorical variables. In order to obtain information on them, each firm was asked to what extent it was affected by these factors. Firms' answers are evaluated in Likert scale from 0 ("not applicable") to 3 ("applies strongly").

The level of intellectual property protection is proxied by pat and tm. These indexes are measured by the scores of the success of legal protection mechanisms for innovations and inventions (patents and trademarks) reported by firms. To deal with the possible endogeneity of these indexes, following Schmidt (2006), we calculate for each firm the average index value across the NACE 3-digit industry code excluding the firm in observation. A higher value of this index for each IPR protection mechanism means that this mechanism achieves better intellectual property protection in the industry. A priori, positive effects of patents and trademarks efficiency in the industry on firms' incentives to imitate and to innovate are expected. Nevertheless, the effect on imitation might be smaller and would be rather indirect via encouraging innovation.

The categorical variable com measures the number of main competitors reported by a firm: more than 15, from 6 to 15, from 1 to 5, or no competitors. Since a firm has a better vision of its own market structure, this indicator measures closer the intensity of market competition. For the estimation 4 dummies are created (com_i, $i = 0, ..., 3$) , where $i = 0$ indicates more than 15, $i = 1$ from 6-15, $i = 2$

from 1 to 5, and $i = 3$ no competitors. Because theoretical results in the literature are ambiguous, we don't have any clear expectations regarding the effect of the number of competitors. Another indicator for competitive pressure is the degree of product substitutability (dif_i). Again, dummies are categorical variables ($i = 0, ..., 3$).

Regarding industry dummies, following OECD taxonomy for NACE Rev.1 codes, we include dummies for 26 aggregated industry sectors.[2] This allows to control for unobserved heterogeneity in innovative performance across sectors. The industry effects on firms' R&D strategy choice might be twofold. On the one hand, industry dummies might capture the technological complexity of knowledge in the industry. The fact that the technology is more advanced in the industry can impede introduction of improved and new products. On the other hand, industry dummies might indicate the level of spillovers from rivals' innovation in the industry. Thus, in industries with higher rate of innovation firms can be more disposed to conduct innovation resulting in the introduction of improved and new products.

From the correlation analysis we find that there are no systematic correlations between explanatory variables that could affect the results of the estimation. However, the inclusion of the number of main competitors as a measure of competitive pressure into the model where the dependent variable is a firm's outcome of product innovation might cause an endogeneity problem. This is because the number of competitors is reported according to the perceptions of firms. Therefore, this regressor can be correlated with unobserved firm characteristics, which allow firms to introduce improved and new products to the market. As a consequence, the number of main competitors is potentially correlated with the error term of the regression. To control for possible endogeneity the present study applies the control function approach proposed by Petrin and Train (2010). The basic idea of the control function approach is to derive an additional regressor that controls for the part of the endogenous regressor that depends on the error term. If this is done, the remaining variation in the endogenous variable is independent of the error, and the estimated model is consistent. The instruments for control function are categorical variables indicating the importance of price and quality competition in the market

[2] The model was also estimated using industry classification NACE Rev 1.1 (Eurocomission). Following it, industries are classified into 5 industry classes (high-tech manufacturing, high-tech services, medium-high- and medium-low-tech manufacturing, and low-tech manufacturing and services) according to R&D intensity. The results are available upon request.

compri, *comqpi*. The estimated control functions for each category of the potentially endogenous regressors *com*1-*com*3 are included into the main regression as cf_com1-cf_com3. Because control functions turn to be significant, this proves that, initially, the variables *com*1-*com*3 were endogenous (see Table 4). Additionally, a robustness check is performed for variables that could be potentially endogenous, concretely, IPR protection efficiency indicators. The result that control functions are not significant suggests these variables to be rather exogenous.[3]

A detailed description of the variables and their expected signs are provided in Table 2. Table 3 presents the descriptive statistics. Over 24% of firms introduced product innovations that were new to their market by 2005, while 29% of firms introduced products that were already known to their market but new for the firm. 47% of firms abstained from innovation. The average firm in the sample has 244 employees, among which, on average 21% of employees have at least higher education. 35% of firms are group members, and 34% of the firms are from Eastern Germany. The similar shares of firms have access markets of different geographical sizes: 26% to local or regional markets in Germany, 28% to German national market, 19% to European and 27% to the world market. 19% of firms reported that they have more than 15 competitors in their markets. A similar share of firms reported to have 6-15 competitors. More than half of the firms in the sample (57%) have claimed to have 1-5 main competitors, while only 4% are monopolists in their markets. Only 9% of firms produce unique products that have no close substitutes, while the rest of firms reported that the products in their markets are substitutable to some extent. The average efficiency of patent protection across industrial sectors is higher than the efficiency of protection by trademarks.

1.4 Empirical model

This section describes the empirical strategy. The statistical model that analyzes firms' R&D strategy choice as a function of firm characteristics and external market parameters should take into account that firms' R&D strategy choices can be threefold: innovation, imitation and no innovation. Given a set of regressors x_{ij}, where $i = 1, ..., I$ indexes firms and $j = 1, ..., J$ indexes regressors, the combination of variables, $\sum_{j=0}^{J} \left(x_{ij}\beta_j \right)$ is used to distinguish between the K categories of the outcome variable. Due to the nature of the dependent variable, a discrete choice model must be employed. The choice of

[3] The estimation results are available upon request.

the model is determined by the relationship between the categories of the dependent variable. One of potentially applicable models is a multinomial logit model. It relies on an assumption that the choices between categories are independent. This assumption is known as IIA (Independence of Irrelevant Alternatives) and it states that the relative probability of preferring one category to another does not depend on the presence or absence of other "irrelevant" alternatives. For example, the relative probability of engaging in imitation or innovation does not change in the absence of other "irrelevant" alternatives. However, it is a very strong assumption for the dependent variable that indicates firms' R&D strategy choices. Actually, the choice of a firm's R&D strategy depends on the amount of resources that it is willing to spend on R&D and on the expected profitability of each strategy. For instance, the amount of resources that is needed to improve already existing products is smaller than the amount of resources needed for the maintenance of an R&D laboratory and radical innovation.[4] Therefore, the choice categories reflect the degree of firms' involvement into innovation activity.

Following this approach, some studies suggest the existence of a natural ordering of categories of the dependent variable according to the degree of firms' "innovativeness" (Link & Neufeld, 1986; Vinding, 2006). Therefore, they propose to employ an ordered logit model. This model is based on two important assumptions. First, it assumes that the same combination of independent variables can be used to distinguish between all levels of the outcome variable. Second, the odds ratio for being in category k or higher, relative to being in group $k-1$ or lower, is assumed to be the same for all k, $2 \leq k \leq K$ (the parallel regression assumption). In the context of our analysis this means that the effect of regressors on the decision to imitate instead of not to innovate is the same as on the decision to innovate instead of to imitate. Since this assumption is not fulfilled, the ordered logit is not applied for the present analysis[5].

A compromise between the two former models is a stereotype logistic regression proposed by Anderson (1984). This model imposes ordering constraints on a multinomial model. In the multinomial logistic model $K-1$ parameters $\widetilde{\beta}_k$, $k = 1, ..., K-1$ are estimated. The stereotype logistic model

[4] Traditionally, application of the multinomial logit model is contrasted by Hausman and Small-Hsiao tests for the IIA assumption. The results of the tests are often contradictory. Therefore, the general advice when using the multinomial logit model is to rely on underlying context of the dependent variable categories. Following this statement, although in the present econometric model tests show a weak evidence in favour if IIA, MNL is not applied in this study.

[5] The LR-test for the pallel regression assumption (Wolfe and Gould, 1998) and a Wald test are performed (Brant, 1990). Both tests reject the parallel regression assumption at 0.01 level.

imposes restriction on the multinomial model by estimating D parameter vectors, where D is between one and $min\,(K-1, j)$. The relationship between coefficients of stereotype model $\beta_d, d = 1, ..., D$ and the multinomial model's coefficients is $\widetilde{\beta}_k = \sum_{d=1}^{D} \phi_{dk}\beta_d$. The parameters ϕ_{dk} are estimated together with parameters β_d. Denote $\eta_k = \theta_k + \sum_{d=1}^{D} \phi_{dk}\mathbf{x}\beta_d$[6], where $\mathbf{x}$ is a row vector of covariates and θ_k are unrestricted constant terms for each equation. The probability of observing outcome k is:

$$\Pr(y_i = k) = \begin{cases} \frac{\exp(\eta_k)}{1+\sum_{k=1}^{K-1}\exp(\eta_k)} & k < K \\ \frac{1}{1+\sum_{k=1}^{K-1}\exp(\eta_k)} & k = K \end{cases}.$$

Using the data of German firms from manufacturing and services sectors the one-dimensional stereotype logistic model is specified as:

$$\eta_k = \theta_k + \phi_k \left(\begin{array}{c} \beta_1 size02 + \beta_2 size02\_2 + \beta_3 hc03 + \beta_4 capint + \beta_5 expint + \beta_6 group + \sum_{i=0}^{3} \beta_{7i} geo_i \\ + \beta_8 ost + \beta_9 pat + \beta_{10} tm + \sum_{i=0}^{3} (\beta_{11i} dif_i + \beta_{12i} com_i) + industry\ dummies \end{array} \right).$$

Due to the low number of categories of the dependent variable, the one-dimensional stereotype logistic model and the two–dimensional stereotype logistic model (which is equivalent to the reparameterized multinomial logistic model) are appropriate choices ($d = 1, 2$). The first category, a firm's decision to abstain from innovation, is chosen as a reference category. When $d = 1$ the estimated relationship between rescaling parameters ϕ_k would indicate the appropriability of the categories ordering. If $\phi_1 \leq \phi_2 \leq ... \leq \phi_K$ holds, the nature of the dependent variable is indeed ordered. For model identification, we must impose the following restrictions on θ_k and ϕ_k: $\theta_0 = \phi_0 = 0$ and $\phi_1 = 1$.

For the ease of interpretation, regression coefficients and their marginal effects are reported. For model evaluation a serie of tests is performed. First, because the model is estimated by maximum-likelihood, likelihood ratio tests are performed. In addition, the χ-squared test is performed to compare the model to the null model (intercept-only). This allows to test if an outcome is higher than what would be expected by chance. Secondly, the validity of ordering in the dependent variable is tested via the estimation of ϕ_k. Third, the predictive ability of the model is compared to the full multinomial model to see if the specification of simplifying constraints of the stereotype model lead to a significant loss of predictive ability.

[6] Originally, Andreson (1984) introduced the model as $\eta_k = \theta_k - \sum_{d=1}^{D} \phi_{dk}\mathbf{x}\beta_d$. The minus sign in front of ϕs makes the interpretation confusing, therefore here the model is rewritten with a plus sign in front of ϕs. The signs of estimated parameters β are reversed correspondingly.

As mentioned above, the stereotype logistic model has a number of advantages. First, it relaxes the proportional regression assumption of the ordered logistic model. Second, it does not impose an ordering restriction on categories, but rather allows to test the appropriability of the ordering. Third, it relies on maximum likelihood estimation of different coefficients for each alternative (multinomial logistic model) and, then, reparameterizes the coefficients. Therefore, it highlights the ordering of categories and reduces the number of parameters for interpretation, without reducing the appropriability of the fit.

1.5 Results

Table 4 provides the estimates (coefficients and average marginal effects) of the stereotype logistic regression. Table 5 reports the marginal effects at means of the number of competitors for a range of patent protection efficiency values and the marginal effects at means of the patent protection efficiency for each category of the number of competitors.

Regarding internal firms' characteristics, the firm size is found to have a positive but decreasing effect on the degree of firms' innovativeness. The quality of human capital, the intensity of capital expenditures and the group membership also have a significant positive impact. The geographical market size has a strong positive effect, which is increasing with market size available for the firm. The location of a firm in former Eastern Germany is related to a lower propensity of the firm to engage in R&D, although, once controlling for other factors, the effect turns to be insignificant.

Remarkably, the estimation results suggest crucial importance of external (market) factors for a firm's R&D strategy choice. The success of legal IPR protection mechanisms, such as patents and trademarks, affects firms' choices to engage in imitative or innovative activity. This fact can have several explanations. First, the reduction of uncertainty about R&D outcomes and future profits due to patent protection plays a very important role in the firms' decision to engage in R&D. This result provides support for the arguments of Arora and Gambardella (1994), Gans and Stern (2003), and Gans et al. (2008). Second, better IPR protection might enhance open innovation. According to the "open innovation paradigm", firms use patents as a channel of knowledge disclosure and dissemination. This benefits other firms in the industry and allows them to be more innovative (Chesbrough, 2003). Finally, no significant effect of IPR protection by trademarks is found.

Competitive pressure is measured by the number of main competitors and the degree of product substitutability. The results show that the oligopolistic market structure with 1-5 main competitors is the one that favour most imitation and innovation. Having no competitors negatively affects firms' innovativeness as compared to very competitive markets. The Wald test is applied for contrast of pairwise equality of categories ($com1$, $com2$ and $com3$). The category with 1-5 main competitors is significantly different from the categories of having no competitors and having 6-15 competitors, while the latter two categories are not significantly different from each other.[7] This suggests the evidence for an "U-inverted" relationship between competitive pressure, as measured by the number of competitors, and firms' incentives to innovate and imitate. Another indicator of competitive pressure, the degree of product substitutability, positively affects firms' innovation though it is not significant.

The marginal effects of the number of competitors are calculated for a range of values of patent protection efficiency. The results suggest that for low levels of patent protection efficiency a small number of competitors (from 1 to 5) positively affects firms' incentives to imitate and to innovate. However, for high levels of patent protection efficiency a small number of competitors affects positively the incentives to innovate while negatively the incentives to imitate. This means that with a high efficiency of intellectual property protection (or high appropriability of knowledge) more firms switch from imitation to innovation. Put it differently, when the number of competitors is small and intellectual property is protected firms are willing to create new products rather than to improve existing ones. Finally, the absence of competitors negatively affects the firms' incentives to innovate and to imitate. However, when the level of patent protection is high, firms are more propense to engage in product improvement (imitation).

The appropriability of the econometric specification is examined in the following ways. First, the correlations in predicted probabilities using the multinomial and stereotype logit are calculated. The probabilities are highly but not perfectly correlated across the two models, supporting that the constraints imposed by stereotype logit hold. Second, the estimates of ϕ_k, which indicate the distance between categories of the dependent variable, are examined. We see that the parameters ϕ_k are monotonically increasing with respect to j, which means that the model is appropriate for the ordinal

[7] First, the comparison of com1 and com2 yields $\chi^2 = 29.72$ and $p - value = 0.0000$. Second, the comparison of com2 and com3 yields $\chi^2 = 19.84$ and $p - value = 0.0000$. Finally, the comparison of com1 and com3 yields $\chi^2 = 0.16$ and $p - value = 0.6911$.

dependent variable and the categories of the dependent variable are ordered in accordance with the impact of the independent variables on them. To see how the effect of market characteristics on firm' R&D strategy choice varies among adjacent categories, we compare $\widehat{\phi}_3 - \widehat{\phi}_2 = 0.653$ (innovation-imitation) and $\widehat{\phi}_2 - \widehat{\phi}_1 = 1$ (imitation-no innovation). This suggests that market characteristics have a stronger impact on the odds of a firm's choice between imitation and no innovation than on the odds of the choice between innovation and imitation. Furthermore, Wald and LR tests are performed to check the distinguishability of dependent variable categories (the equality of ϕ_k). Because the hypothesis that all parameters ϕ_k are equal can be rejected at 0.01 significance level, we conclude that the categories of the dependent variable are distinguishable. The overall predictive ability of the model is similar to that of the full multinomial logit model and is over 57%.

1.6 Robustness check: an analysis of firms' R&D strategies at the industry level

This section extends the analysis of firms' R&D strategy choice at an industry level, investigating the determinants of overall innovative performance of the industries. Dependent variables of the analysis ($str1$, $str2$ and $str3$) represent the number of firms in the industry that were, correspondingly, no-innovators, imitators and innovators in 2005. Another interpretation of these variables is the degree of "absence of innovation", "imitation" and "innovation" in the industry. Then, the count of firms in $str1$ refers to no-innovation, in $str2$ to imitation or incremental innovation (the improvement of already existing products), and in $str3$ to more radical innovation (introduction of products that did not exist in the market before).

Similarly to the analysis at a firm level, the two categories of independent variables are included into our empirical model, the variables that measure internal firm characteristics in the industry and external market factors. Internal firm characteristics are continuous and categorical variables in the survey. Continuous variables are aggregated as median or mean values at the industry level. Accordingly, continuous independent variables are the 25th, 50th and 75th percentiles of the firm size in the industry ($size25$, $size50$ and $size75$), the mean values of human capital quality ($hc03$), capital intensity ($capint$) and export intensity ($expint$). Categorical variables are aggregated at an industry level as counts of firms that belong to a group ($group$), have access to the local and regional ($geo1$), the German-wide (*geo*2), the European (*geo*3) and the world (*geo*4) market, and are located in the territory of former Eastern Germany (*ost*).

The market characteristics employed are the average efficiency of IPR protection by patents and trademarks (*pat* and *tm*) and the industry concentration measured by the Herfindahl-Hirschman index (*hh*). Following the firm-level analysis, positive effects of *pat* and *tm* are expected on the number of firms that engage in R&D (*str*3) and, accordingly, negative effects are expected on the number of firms that abstain from innovation (*str*1). The concentration index *hh* is computed using total shares of sales at the three-digit NACE level, although it is an imperfect measure of the degree of competition.

Regarding industry dummies, the model was estimated using industry classification NACE Rev 1.1 (Eurocomission). Following it, industries are classified into 5 industry classes (high-tech manufacturing, high-tech services, medium-high- and medium-low-tech manufacturing, and low-tech manufacturing and services) according to their R&D intensity in Europe. This allows to control for an unobserved heterogeneity in the innovative performance across sectors. In Table 6 the summary of firm characteristics and market parameters in German manufacturing and services industries in the year 2005 is displayed. Innovative performance of German industries is consistent with European industry sectors classification. Most innovative firms belong to high-tech sectors while the number of non-innovating firms is the highest in low-tech sectors. By the number of employees firms in high-tech sectors are on average larger than in low-tech, and the smallest are firms from high-tech services. Higher shares of firms from high-tech sectors are located in former Eastern Germany. High-tech sectors are on average slightly more concentrated. Regarding the efficiency of IPR protection, the firms from high- and medium-high-tech manufacturing attribute the highest efficiency of IPR protection to patents and trademarks, while the lowest scores come from high-tech services sectors.

Since the three dependent variables of the analysis are the counts of firms that abstain from innovation, imitate and innovate, in each industry the count data model is employed. Concretely, for each of the dependent variables *str*1-*str*3 we estimate the negative binomial model.[8] It assumes that the observed count of observation i is drawn from a negative binomial distribution with mean

[8] Due to significant evidence of overdispersion for each of three regressions tested by the Likelihood-ratio test ($\overline{\chi}^2$ (01) $= 174.28, 73.11, 54.23; p < 0.01$) the negative binomial regression model is preferred to the Poisson regression.

$\mu_i = E(y_i \mid x_i) = \exp(\mathbf{x}_i\beta)$. The negative binomial distribution of observations is assumed to be

$$\Pr(y \mid x) = \frac{\Gamma\left(y+\alpha^{-1}\right)}{y!\Gamma\left(\alpha^{-1}\right)}\left(\frac{\alpha^{-1}}{\alpha^{-1}+\mu}\right)^{\alpha^{-1}}\left(\frac{\mu}{\alpha^{-1}+\mu}\right)^{y},$$

where $\Gamma()$ is the gamma function and the parameter α determines the degree of dispersion in the predictions. The dispersion of observations is assumed to be NB2 (Cameron and Trivedi, 1986), which is most often used in applied research:

$$Var(y_i \mid \mathbf{x}) = \mu_i + \alpha\mu_i^2$$

The model is specified as:

$$\mu(str_k) = \exp\begin{pmatrix} \beta_1 size25 + \beta_2 size50 + \beta_3 size75 + \beta_4 hc03 + \beta_5 capint + \beta_6 expint + \beta_7 group \\ +\beta_8 ost + \sum_{i=0}^{3}\beta_{9i} geo_i + \beta_{10} hh + \beta_{11} pat + \beta_{12} tm + industry\ dummies \end{pmatrix},$$

where $k = 1, ..., 3$.

However, in the set of equations with dependent variables *str*1-*str*3 the error terms in the regression equations are correlated. Therefore, the covariance matrix is estimated using the Eicker-Huber-White-sandwich covariance estimator to a set of equations (Eicker 1963; Huber 1967; White 1980). This makes standard errors valid in the presence of cross-equation correlations or heteroskedasticity.

For the ease of interpretation of regression coefficients incidence-rate ratios are computed. If $E(y \mid \mathbf{x}, x_j)$ is defined as the expected count for a given $\mathbf{x}$, where x_j is explicitly observed, and $E(y \mid \mathbf{x}, x_j + 1)$ as the expected count after increasing x_j by 1, then

$$\frac{E(y \mid \mathbf{x}, x_j + 1)}{E(y \mid \mathbf{x}, x_j)} = e^{\beta_j}$$

is an incidence-rate ratio. It can be interpreted as given the increase of x_j by 1 the expected count increases by a factor of e^{β_j}, holding all other variables constant. In addition, the percentage changes in the dependent variable given a unit change of the regressors are reported (Table 7).

The results show that the firm distribution by size is not related to the firms' R&D strategy choices. Only the 25th percentile of firm size in the industry is weakly negatively related to the number of imitating and innovating firms in the industry. The mean quality of human capital in the industry positively affects the number of innovators, while having a negative impact on the number of non-innovating firms. We see that low capital intensity is associated to massive imitation (or incremental innovation) in industries. Low export intensity leads to less innovation in industries. The number of firms located in former Eastern Germany is negatively related to the count of innovating and imitating firms.

The industry level analysis stresses a positive effect of an IPR protection efficiency (by means of patents and trademarks) on the number of innovators and, correspondingly, a negative effect on the number of firms that abstain from innovation. It supports the results of the firm level analysis. However, no significant effect on the number of imitators is found. The concentration index negatively affects the number of innovating, imitating and non-innovating firms in industries. However, its effect is lower with respect to the number of innovative firms, indicating that more concentration can lead to more innovation.

Finally, regarding industry technological classes, firms' innovative performance in German manufacturing industries is close to the European classification. Noteworthy, the dummy for sectors that belong to high-tech services is positive and significant for non-innovating and imitating firms. This indicates that services firms are oriented on rather incremental improvements in their products than on radical change.

1.7 Discussion

The results of this paper extend previous findings on the firms' choice between innovation and imitation. First, this study uses a larger sample of firms from manufacturing and services sectors than the predecessors (Link and Neufeld, 1986; Vinding, 2006). Second, the results of previous studies are contradictory. Specifically, the former finds that market power is crucial for firms to engage into innovation and imitation. Conversely, the latter finds that an increase in competitive pressure enhances innovation. However, both studies use competition measures that can be endogenous to the dependent variables. The present study controls for potential endogeneity when using the measures of competitive pressure and suggests a non-monotonic effect of competitive pressure on firms' incentives to imitate and innovate. A small number of competitors is found to be optimal for innovative performance of an industry in terms of new product introduction. In addition, this effect varies depending on the IPR protection efficiency.

This paper relates to several theoretical studies. The results support Boldrin and Levine (2008) who argue that IPR protection is a good mechanism for enhancing innovation. The present paper goes further analyzing how this effect depends on the level of competition a firm faces. Opposite to Vives (2008), empirical evidence on German firms suggests that an increase in market size has a non-ambiguous positive effect on the introduction of new products. Finally, our results contradict theoretical findings by Zhou (2009). Using a standard oligopoly framework he shows that intensified competition measured by an increase in the number of competitors always dampens innovation. Under a moderate level of competition, weak IPR protection (or a high exogenously given level of spillovers) increases firms' incentives to innovate. This might result from the fact that in Zhou (2009) the model does not account for possible changes in R&D strategies chosen by firms (innovation and imitation) when it becomes more profitable to switch from the current strategy. When the level of spillovers is high (or the level of IPR protection is weak), former innovators might find it more profitable to switch to imitation, increasing competition among imitators. Contrary to Zhou (2009), this paper finds that a small number of competitors can stimulate both product innovators and imitators. IPR protection to a large extent affects a firms' choice to innovate and, indirectly, has a small positive effect on product improvement by imitators through an increased activity of innovators. Therefore, when looking at the effect of competitive pressure and intellectual property protection, it is essential to model a firms' R&D strategy choice as endogenous.

1.8 Concluding remarks

This paper analyzes how firms choose their R&D strategies as a function of external factors such as spillovers and competitive pressure. To the best of my knowledge, despite a few empirical studies focusing on the choice between innovation and imitation (Link and Neufeld, 1989; Vinding, 2006), until now, external and internal parameters that are both important for such a firm decision have not been analyzed jointly. I explicitly consider that firms may have different innovation strategies (innovate, imitate or not innovate) and analyze how IPR protection, product differentiation and competitive pressure jointly affect firms' R&D strategy choice.

The results show that the patent protection efficiency positively affects the propensity of firms to imitate or to innovate. A decrease in competitive pressure from many to few competitors positively affects the propensity of firms to improve already existing products, and to introduce market novelties.

This effect varies with patent protection efficiency. When it is low, both innovation and imitation are enhanced, while when it is high, imitation is reduced and innovation is enhanced. A further decrease in competitive pressure from few competitors to no competitors (monopoly) diminishes innovation and favours imitation.

Once the factors that affect firm R&D strategy choice are identified, another crucial question arises. Is it efficient to have much imitation in the markets or is it better to restrict imitation providing monopoly power to innovators? This question is addressed in recent theoretical studies. For instance, Konig et al. (2012) introduce the endogenous choice between innovation and imitation into an endogenous model of technological change, productivity growth and technology spillovers. Fostering only innovation increases the inequality in the industry, which lowers overall economic performance. Increased imitation in the absence of innovation doesn't contribute to productivity growth. Therefore, they suggest to enhance both in-house innovation and technology diffusion through imitation. However, further theoretical research is needed to analyze social welfare implications of the innovation/imitation balance under different market structures with endogenous R&D strategy choice.

The findings of this study suggest to look beyond R&D expenditures and take into account that firms might change their R&D strategy when there are changes in market parameters, which in turn affects overall innovative performance of the industries. In addition, the present analysis derives a link between IPR protection and competition policy. The two policies must be tightly coordinated because IPR protection and competitive pressure jointly affect firms' R&D strategy choices. In particular, the improvement of patent protection efficiency or the introduction of longer patent duration is positive for any level of competition. However, in markets with few competitors it raises firms' incentives to innovate and decreases firms' incentives to imitate. Finally, in markets where firms have almost monopoly power an increase in patent protection efficiency incites the introduction of improved products (imitation) while it discourages innovation.

Several limitations of the present study call for further research on this topic. First, due to data availability this study adopts a static perspective. An analysis from a dynamic perspective (using panel data) would allow to account for firm-specific unobserved heterogeneity and would decrease the potentially existing bias due to omitted variables. Second, the analysis of sectorial patterns of firms' R&D strategy choice is obstructed due to the small number of observations. An analysis within sectors would allow for sector-specific R&D and competition policies. Although implementation of sector-specific policies is a difficult task, it would increase the efficiency of public intervention.

N	Industry	No-Innovation (%)	Imitation, %	Innovation, %	TOTAL firms
	Manufacturing	474 (36.49%)	389 (29.95%)	436 (33.56%)	1,229
0	Agriculture / Farming	7 (50.00%)	4 (28.57%)	3 (21.43%)	14
1	Mining	18(69.23%)	5(19.23%)	3(11.54%)	26
2	Food / Tobacco	35 (46.67%)	25 (33.33%)	15 (20.00%)	75
3	Textiles	27 (45.00%)	15 (25.00%)	18 (30.00%)	60
4	Wood / Paper	07 (49.65%)	44 (31.21%)	27 (19.59%)	141
5	Chemicals	18 (17.82%)	29 (28.71%)	54 (53.47%)	101
6	Plastics	40 (41.67%)	31 (32.29%)	25 (26.04%)	96
7	Glass / ceramics	21 (41.18%)	9 (17.65%)	21 (41.18%)	51
8	Metals	115 (53.74%)	55 (25.70%)	44 (20.56%)	214
9	Machinery	33 (21.57%)	54 (35.29%)	66 (43.14%)	153
10	Electrical equipment	24 (19.20%)	45 (36.00%)	56 (44.80%)	125
11	Medical and other instruments	12 (9.76%)	40 (32.52%)	71 (57.72%)	123
12	Transport equipment	17 (34.00%)	16 (32.00%)	17 (34.00%)	50
13	Furniture	37 (52.86%)	17 (24.29%)	16 (22.86%)	70
	Services	670 (57.81%)	323 (27.87%)	166 (14.32%)	1,159
14	Wholesale	56 (65.12%)	19 (22.09%)	11 (12.79%)	86
15	Retail / Automobile	29 (85.29%)	4 (11.76%)	1 (2.94%)	34
16	Transport / Communications	106 (66.25%)	41 (25.63%)	13 (8.13%)	160
17	Banking / Insurance	35 (38.89%)	42 (46.67%)	13 (14.44%)	90
18	IT / Telecommunications	27 (23.89%)	56 (49.56%)	30 (26.55%)	113
19	Technical services	95 (44.81%)	60 (28.30%)	57 (26.89%)	212
20	Firm-related services	44 (51.76%)	25 (29.41%)	16 (18.82%)	85
21	Real estate / Renting	37 (68.52%)	12 (22.22%)	5 (9.26%)	54
22	Construction	40 (85.11%)	7 (14.89%)	–	47
23	Energy / Water supply	79 (80.61%)	16 (16.33%)	3 (3.06%)	98
24	Film / Broadcasting	21 (63.64%)	7 (21.21%)	5 (15.15%)	33
25	Other services	101(68.71%)	34 (23.13%)	12 (8.16%)	147
	TOTAL	1,144 (46.54%)	712 (28.98%)	602 (24.49%)	2,458

Table 1: The patterns of innovative activity in German manufacturing and services industries (2488 observations, year 2005)

Variable	Label	Expected Sign (Imit/Inn)
Dependent variables		
STR	Firms' R&D strategy: 0=non-innovation, 1=imitation or 2=innovation.	
Independent variables		
Firm characteristics:		
size02	Size of the firm in 2002, measured as a number of employees	+
hc03	A firm's human capital measured by the proportion of all employees who have a university degree or other higher education qualification in 2003	+
capint	Intensity of capital expenditures in 2003, normalized by overall turnover in 2003	+
expint	Turnover from export in 2002, normalized by overall turnover in 2002	+
group	Firms that belong to the group of firms: 0=no; 1=yes	+
geo	Geographical size of the market availabe for the firm: 0=local or regional market, 1=nation-wide market in Germany, 2=EU and EFTA countries and EU candidates, 3=world market	+
ost	Firms from the former Eastern Germany: 0=no, 1=yes	?
Market characteristics:		
pat, tm	The success of legal protective mechanisms for innovations and inventions (patent, trademark): the sum of listed factors evaluated as 0=not applicable, 1=hardly applies, 2=rather applies, 3=strongly applies, rescaled such that it varies between 0 (minimum level) and 1 (maximum level). For each firm this value is calculated in its 3-digit NACE Rev.1 industrial code excluding the firm itself.	+
com	The number of main competitors: 0=no competitors,, 1=from 1 to 5, 2=from 6 to 15, 3 =more than 15	+/-
dif	Products of competitors can easily be substituted by products of the firm: 0=not applicable, 1=hardly applies, 2=rather applies, 3=strongly applies	?
Instruments:		
compr	Importance of price competition on the main market of the firm: 1 = very fierce, 2 = fierce, 3 = medium, 4 = weak, 5 = very weak, 6 = not significant.	
comqp	Importance of quality competition on the main market of the firm: 1 = very fierce, 2 = fierce, 3 = medium, 4 = weak, 5 = very weak, 6 = not significant.	

Table 2: Description of variables

Variable	Mean	Std. dev.	Med	Min	Max
STR	0.780	0.807	1	0	2
size02	243.603	729.325	46	0	4618
hc03	20.792	24.690	10	0	100
capint	0.062	0.127	0.023	0	1.01
expint	0.139	0.233	0	0	0.906
group	0.350	0.477	0	0	1
ost	0.336	0.473	0	0	1
pat	0.533	0.566	0.273	0	3
tm	0.429	0.326	0.375	0	3
Variable	0	1	2	3	
dif	9.42%	23.12%	43.57%	23.90	
com	19.44%	19.90%	56.85%	3.81%	
geo	26.42%	28.03%	18.52%	27.02%	

Table 3: Descriptive statistics (2176 observations, year 2005)

	Model 1		**Marginal effects**		**Model 2**		**Marginal effects**	
	Coef.	(Std. Err.)	ME Imit.	ME Inn.	Coef.	(Std. Err.)	ME Imit.	ME Inn.
			Firm characteristics					
size02	0.001**	0.000	0.000**	0.000**	0.001**	0.000	0.000**	0.000**
size02 _2	−0.000**	0.000			−0.000**	0.000		
hc03	0.012**	0.002	0.001**	0.002**	0.014**	0.002	0.001**	0.002**
capint	1.040**	0.314	0.061**	0.180**	0.619+	0.363	0.042+	0.098+
expint	0.225	0.225	0.013	0.039	−0.121	0.261	−0.008	−0.019
group	0.249**	0.090	0.015*	0.043**	0.145	0.105	0.010	0.023
geo0	*(b.c.)*							
geo1	0.303*	0.123	0.018*	0.052*	0.618**	0.158	0.042**	0.098**
geo2	0.703**	0.125	0.041**	0.122**	0.861**	0.147	0.058**	0.137**
geo3	0.708**	0.113	0.042**	0.123**	0.979**	0.137	0.066**	0.155**
ost	−0.137+	0.073	−0.008+	−0.024+	−0.094	0.081	−0.006	−0.015
			Market characteristics					
pat	0.385*	0.164	0.023*	0.067*	0.605**	0.172	0.041**	0.096**
tm	0.248	0.162	0.015	0.043	-0.001	0.175	−0.000	−0.000
com0	(b.c.)							
com1	0.013	0.110	0.001	0.002	−0.417	0.535	−0.028	−0.066
com2	0.251**	0.090	0.015**	0.043**	3.238**	0.703	0.218**	0.514**
com3	−0.158	0.216	−0.009	−0.027	−0.745*	0.365	−0.050+	−0.118*
dif0	(b.c.)							
dif1	0.224	0.168	0.013	0.039	−0.034	0.206	−0.002	−0.005
dif2	0.238	0.165	0.014	0.041	0.151	0.195	0.010	0.024
dif3	0.018	0.180	−0.001	−0.003	0.106	0.217	0.007	0.017
Industry dummies (joint significance)								
	$\chi^2\,(25)$	107.05**			$\chi^2\,(19)$	93.73**		
$(\phi_1 = 0, \phi_2 = 1)\ \phi_3$	1.758**	0.112			1.652**	0.101		
$(\theta_1 = 0)\ \theta_2$	−1.417**	0.491			−2.224**	0.584		
θ_3	−2.852**	0.849			−4.106**	0.937		
cf_ com1					0.174	0.204		
cf_ com2					−1.447**	0.334		
cf_ com3					0.105*	0.047		
N obs.	2488				2176			
Log-likelihood	−2190.9				−1938.5			
Wald chi-squared	465.92				507.80			
% pred. prob.	57.3%				57.2%			

Note: +, * and ** indicate statistical significance at 10, 5 and 1% level.

Table 4: Stereotype logit regressions on str (at the firm level)

A decrease in comp. pressure (cat. com2 with respect to cat. com0)		
pat	dy/dx Imitation	dy/dx Innovation
0.0	0.442**	0.536**
0.5	0.343**	0.641**
1.0	0.203**	0.720**
1.5	0.046	0.763**
2.0	−0.103	0.768**
2.5	−0.223+	0.740**
3.0	−0.307*	0.689**
A decrease in comp. pressure (cat. com3 with respect to cat. com0)		
pat	dy/dx Imitation	dy/dx Innovation
0.0	−0.102*	−0.123*
0.5	−0.078+	−0.147*
1.0	−0.047+	−0.166*
1.5	−0.011	−0.176*
2.0	0.024	−0.177*
2.5	0.051	−0.170*
3.0	0.071+	−0.159*
An increase in IPR protection efficiency		
com	Imitation dy/dx	Innovation dy/dx
0	0.069**	0.027*
1	0.082**	0.090*
2	−0.044*	0.130**
3	0.087**	0.067*

Table 5: Marginal effects of 1) the number of competitors for a range of patent protection efficiency values; 2) patent protection efficiency for the categories with the number of competitors in Model 2

Industry	HTM	MHTM	MLTM	HTS	Other sectors
No-Innovation (%)	60 (18%)	147 (25%)	310 (49%)	770 (53%)	1079 (65%)
Imitation, (%)	107 (32%)	192 (33%)	160 (25%)	418 (29%)	377 (23%)
Innovation, (%)	170 (50%)	252 (43%)	159 (25%)	270 (18%)	217 (13%)
Average firm size	3899.2	2506.5	2144.5	283.6	377.9
Firm size p25	22.4	242.5	110.7	34.1	129.9
Firm size p50	78.1	1330.4	387.0	83.5	182.4
Firm size p75	377.3	3961.9	2452.2	301.1	319.2
Average cap.intensity	0.03	0.03	0.03	0.09	0.04
Average exp.intensity	0.22	0.29	0.17	0.00	0.08
Firms located in former GDR (%)	122 (36%)	171 (29%)	207 (33%)	546 (37%)	589 (35%)
Firms belong to the group (%)	129 (38%)	290 (49%)	233 (37%)	455 (31%)	537 (32%)
N firms with access to local or regional market, %	30 (9%)	35 (6%)	92 (15%)	552 (38%)	748 (45%)
N firms with access to German-wide market, %	80 (24%)	103 (17%)	184 (29%)	633 (43%)	484 (29%)
N firms with access to EU market, %	62 (18%)	148 (25%)	165 (26%)	153 (10%)	274 (16%)
N firms with access to int. market, %	174 (52%)	327 (55%)	226 (36%)	186 (13%)	239 (14%)
Av. efficiency of IPR protection					
by patents	1.50	1.45	0.77	0.14	0.30
by trademarks	0.87	0.74	0.53	0.37	0.47
Competitive pressure					
Herfindahl-Hirshmann	0.48	0.45	0.32	0.45	0.42

Table 6: The description of firm and market characteristics by industry classes (180 observations, year 2005).

	Dependent variables					
	str1		str2		str3	
	e^{β}	%	e^{β}	%	e^{β}	%
Firm characteristics						
size25	0.999	−0.1	0.999*	−0.1	1.000+	−0.0
size50	0.999	−0.1	1.000*	0.0	1.000	0.0
size75	1.000	0.0	1.000	0.0	1.000+	−0.0
hc03	0.981**	−1.9	1.001	0.1	1.010	1.0
capint	0.814	−18.6	0.599**	−40.1	0.983	−0.3
expint	0.222**	−77.8	0.552	−44.8	1.067	1.1
group	1.057**	5.7	1.053**	5.3	1.040*	4.0
ost	1.025*	2.5	1.005	0.5	0.996	−0.4
geo1	0.990	−1.0	0.999	−0.1	1.006	0.6
geo2	0.995	−0.5	1.021	2.1	1.020	2.0
geo3	0.999	−0.1	1.000**	−0.0	1.015	1.5
Market characteristics						
hh	0.248**	−74.3	0.292**	−70.8	0.326**	−67.4
pat	0.650**	−28.2	1.062	6.2	1.300*	30.0
tm	0.807*	−20.4	1.139	13.9	1.390*	39.0
Industry class dummies						
MLTM	1.197+	19.7	1.024	2.4	1.487**	48.7
MHTM	1.170	17.0	1.409+	40.9	1.578*	57.8
HTM	1.022	2.2	1.548+	54.8	2.021**	102.1
HTS	1.322+	32.2	1.469*	46.9	1.316	31.6
N obs.	180		180		180	
LR chi2(21)	306.26		237.30		235.61	
Pseudo R2	0.2383		0.2203		0.2332	

Note: +, * and ** indicate statistical significance at 10, 5 and 1% level.

Table 7: Negative binomial regressions on str1 - str3 (at the industry level)

CHAPTER II

INNOVATION OR IMITATION? THE EFFECT OF SPILLOVERS AND COMPETITIVE PRESSURE ON FIRMS' R&D STRATEGY CHOICE

2.1 Introduction

The economic literature on innovation has provided two confronting views concerning the relationship between innovation and imitation. According to the Schumpeterian view, imitation dampens innovation as it renders innovative efforts unprofitable. In this view, intellectual property rights (IPR) protection is a necessary mechanism that provides incentives for firms to engage in R&D and encourages technology transfer between firms. Therefore, a strong protection of intellectual property rights would be the optimal R&D policy (Arora and Gambardella, 1994; Gallini and Scotchmer, 2002; Gans and Stern, 2003; Gans et al., 2008). This view has recently been challenged by Aghion et al. (2001), Bessen and Maskin (2009) and Zhou (2009) who show that stronger imitation fosters innovative efforts by incumbent firms. So, IPR protection can block the future development of technologies. Looking at these contradictory views the question of what should be the optimal balance of innovation and imitation arises. Certainly, the evidence on innovative activity at the firm level suggests elevated heterogeneity in innovative performance within as well as across markets. The heterogeneity observed is the result of firms' decisions to engage in R&D or to abstain from own R&D and imitate the outcomes of innovators. This indicates that any policy intervention might not only affect the level of a firm's R&D performance but also the strategies adopted by firms. In this paper we develop a model that allows us to analyze how external market parameters such as the intensity of IPR protection, market competition, or the degree of product differentiation affect firms' R&D strategy choices.

Theoretical studies have analyzed the effect of possible imitation on innovative incentives in two frameworks, economic growth models (Grossman & Helpman, 1991; Aghion & Howitt, 1992; Palokangas, 2011) and oligopolistic competition models (Zhou, 2009). For instance, in Palokangas (2011) the optimal patent protection is determined by the taste for variety that increases efficiency of consumption and the level of spillovers, therefore, given the low level of spillovers more competition is socially desirable. However, most of this literature assumes that innovators and imitators are exogenously given. Exceptions are Segestrom (1991) and Amir and Wooders (2000). Applying an economic growth model, Segestrom (1991) allows firms to participate in both innovative and imitative R&D races. In the steady-state, firms' equilibrium R&D strategies depend on the distribution of previous R&D outcomes and the relative price of imitation. Firms are found to benefit more from imitation in industries with a single leader, while in industries with several leaders innovation is a more profitable strategy. In a standard oligopoly framework, Amir and Wooders (2000) show that, in equilibrium, firms choose their R&D strategies asymmetrically which gives rise to an innovator/imitator configuration in the market. Surprisingly, until now no paper has analyzed the welfare and policy implications of alternative market structures on innovation incentives when firms endogenously choose their R&D strategy.[1] In this paper we develop a theoretical model that explains how firms endogenously choose their R&D strategy between innovation and imitation and analyze how market characteristics determine firms' R&D strategy choices and the welfare implications of alternative IPR protection regimes. Contrary to Amir and Wooders (2000), spillovers from innovators to imitators are modelled as in d'Aspremont and Jacquemin (1988) and not in an all-or-nothing probabilistic fashion. Furthermore, regarding the welfare implications of market dominance we find that a positive effect on social welfare is obtained when both the firm with a larger market share (the dominant firm) and the firm with a smaller market share engage in R&D. However, when the smaller firm to abstain from innovation, the welfare effect is negative. This happens when products are highly differentiated and spillovers are low.

Our set-up is a two-stage Cournot model with differentiated products and strategic R&D choice. In stage 1, firms decide simultaneously what R&D strategy to apply, innovation or imitation. In stage 2, firms compete in quantities with differentiated products, conditional on their R&D strategy choice. We characterize the equilibria of this game and show how different innovation patterns that depend on the extent of spillovers, asymmetries between firms and competitive pressure arise. Three types of equilibria are obtained: equilibria in which all firms innovate, equilibria in which firms choose

[1] Segestrom (1991) assumes a unique market structure for his R&D innovation and imitation races. Amir and Wooders (2000) allow for different market structures but their welfare implications are focused on research joint ventures.

asymmetric R&D strategies, and equilibria in which no firm innovates. We find that the efficiency of IPR protection positively affects firms' incentives to engage in R&D, while competitive pressure has a negative effect. In addition, smaller firms are found to be more likely to become imitators when products are homogenous and the level of spillovers is high. Regarding social welfare, our results indicate that the strengthening of IPR protection can have an ambiguous effect. If a market is characterized by a high rate of innovation, a reduction of IPR protection can discourage innovative performance substantially. However, a reduction of IPR protection can also increase social welfare because it may induce imitation. Furthermore, regarding the welfare implications of market dominance we find that a positive effect on social welfare is obtained when market dominance means that the larger firm becomes an innovator or when it does not affect the firms' R&D strategies. However, when more market dominance causes the smaller firm to abstain from innovation, the welfare effect is negative. This happens when products are highly differentiated and spillovers are low.

The main policy implication derived from our analysis is that a common IPR protection policy for all markets might be inappropriate. This is because a policy that is beneficial for a certain type of market might discourage innovation and technological progress in another with different characteristics. The analysis of spillovers on social welfare shows that a reduction of IPR protection, intended to induce imitation, can discourage innovative performance substantially in markets that are characterized by with a high share of innovators /with many innovating firms/where many firms previously chose to innovate (this is to address a comment that the number of innovators is a consequence rather than fundamental. if reformulated, it shows that we understand the high rate of innovation as an outcome). Then, an additional reduction of IPR protection induces more imitation and increases welfare. However, after a certain point, the reduction of patent protection completely discourages innovation and therefore reduces social welfare. Moreover, an IPR protection policy must be tightly coordinated with the competition policy. This is because external parameters such as IPR protection and competitive pressure jointly affect the firms' R&D strategy choice.

This paper is related to a large literature on the relationship between market structure and innovation strategy. Specifically, it is related to two strands in the literature. The first strand analyzes how firms' R&D investments are affected by market competition. Pioneer works in this field are those of Schumpeter (1934 and 1942) who argues that, on the one hand, market pressure may foster firms' innovation. But, on the other hand, market pressure may also decrease firms' R&D investments because monopoly power of larger firms acts as a major accelerator of technological progress. Actually, there is still no accordance on this Schumpeterian debate in theoretical and empirical studies. For example, some authors argue that more intensive market competition decreases a firm's incentives for innovation because when advantages from innovation are temporary, only sufficient market power guarantees that firms invest in R&D (Arrow, 1962; Futia, 1980; Gilbert and Newbery, 1982; Reinganum, 1983; or Zhou, 2009). This argument is supported by empirical studies that find that market concentration increases the pace of innovative change. For instance, Henderson and Cockburn (1996) show that large firms in the US pharmaceutical industry perform R&D more efficiently, as they can enjoy scale and scope economies. Using patent data of UK manufacturing firms, Cefis (2003) finds that, due to innovative effort, the contribution of large firms to aggregated industrial performance is above the industry mean. On the other hand, market concentration is also argued to have a dampening effect on innovation because more intensive competition acts as an important incentive for firms to innovate (Dasgupta and Stiglitz, 1980). Again, this theoretical argument is supported by empirical evidence (Geroski, 1990; Blundell et al., 1999). These contradictory results led to the hypothesis that the effect of market competition on firms' innovative efforts is non-monotonic. For example, Boone (2000) finds that when competition is weak, the incentives of less efficient firms to innovate increase. However, when competition becomes more intense, the incentives of efficient firms to innovate grow. Aghion et al. (2005) suggest the existence of an inverted-U relationship. Both, a low or high level of competition provide low incentives to innovate while a medium level of competition fosters innovation of firms operating on a similar technological level ("neck-and-neck firms"). On the contrary, Tishler and Milstein (2009) find that R&D investments decrease with competitive pressure. However, at a certain level of competition firms engage in "R&D wars" and spend excessively on R&D. Our results also indicate a non-monotonic relationship between firm innovation and competitive pressure. They highlight the importance of factors such as IPR protection and product differentiation for this relationship. Concretely, when the products are highly differentiated and IPR protection is efficient, an increase in the number of competitors increases overall innovative performance in the market. On the contrary, if the products are homogenous and spillovers are high, an increase in competitive pressure can decrease the number of firms that choose to innovate.

The second strand of the literature to which this paper is related are studies that, contrary to the above literature that assume that all firms are innovators, allow for heterogeneity in firms' R&D strategies by distinguishing between firms that innovate and those that imitate innovators. As empirical evidence suggests, most markets are characterized by an elevated heterogeneity of R&D activities. So, in most markets we find a core of firms that are persistent innovators while other firms either are occasional innovators or imitators (Cefis and Orsenigo, 2001; Cefis, 2003). Czarnitzki et al. (2008) find that, depending on a firm's role in the market, competitive pressure might have a different effect on innovative effort. For example, while entry pressure decreases the average investment per firm, it increases innovative effort of market leaders. In theoretical studies (Grossman and Helpman, 1991; Aghion and Howitt, 1992; Zhou, 2009), imitation is shown to foster the innovation activity of technological leaders. This finding challenges the common view that patent protection should be strengthened. In fact, some studies argue that strong IPR protection may slow down the development of countries and decrease world welfare and consumer surplus (Helpman, 1993; Bessen and Maskin 2009; Che et al., 2009; Fershtman and Markovich, 2010). Additionally, Braguinsky et al. (2007) find that the relationship between innovation and imitation itself depends on other factors such as the maturity of an industry. When the industry is young and small, innovators do not have incentives to prevent imitation. But when the industry expands, innovative effort decreases because of imitation pressure. The results in this paper contribute to this literature first, by showing how different market characteristics give rise to different innovator/imitator configurations. Second, the results show that an increase of IPR protection can both increase and decrease social welfare depending on the underlying market characteristics. This result reconciles the confronting views on the role of patent protection strength.

The rest of the paper is arranged as follows. Section 2 presents a theoretical Cournot duopoly model of R&D strategy choice. Section 3 includes extensions for the cases of asymmetric firms and more than two-firm competition. Section 4 discusses the policy implications of our findings. Proofs are in the Appendix.

2.2 A duopoly model

In this section we develop a two-stage Cournot duopoly model with differentiated products and strategic R&D choice. In stage 1, firms decide simultaneously what R&D strategy to apply, innovation or imitation. In stage 2, firms compete in quantities with differentiated products, conditional on their R&D strategy choice. We assume that each firm produces a single good and that the two goods are substitutes. The inverse demand function of good i is:

$$p_i = a - bq_i - dq_j, \quad i, j = 1, 2, i \neq j, \tag{1}$$

where p_i is the price and q_i is the quantity of good i. We assume that $a > 0$, $b > 0$, $d \geq 0$. Furthermore, the absolute value of the own-price effect on the quantity demanded is assumed to be higher than the corresponding effect of the price of the substitute, thus $b - d \geq 0$.

The R&D strategy at stage 1 is realized by the choice of a binary variable x_i, where $x_i = 1$ stands for the firm's decision to engage in R&D and $x_i = 0$ means that the firm abstains from innovation. R&D investment allows a firm to reduce its unit production cost c by the amount γx_i at cost Kx_i, where $\gamma \in [0, 1]$ and $K > 0$ are known constants. However, if a firm abstains from investing in R&D at stage 1, due to spillovers, it's production cost still is reduced by imitating the rival's R&D outcomes.[2] Concretely, if firm i innovates and firm j abstains from innovation but decides to imitate, the unit cost reduction for firm j is $\sigma\gamma x_i$. The parameter σ indicates to what extent a cost reduction of firm i allows firm j to reduce its own production costs. We assume that $\sigma \in [0, 1]$, where $\sigma = 0$ indicates that there are no spillovers and $\sigma = 1$ means that firm j obtains the same cost saving as firm i without any additional investment. Here we focus on asymmetric spillovers (from the innovator to the imitator), which is justified if the cost-reducing innovation is achieved following the order. Innovators move first, choosing the R&D program. Imitators move second, enjoying the know-how flows from more advanced rivals (see Bower and Christensen, 1995; De Bondt, 1996; Amir and Wooders, 2000). These asymmetric spillovers can be interpreted as an inverse of patent length or imitation lag. Resuming

[2] Notice, that the assumption that imitation is costless is not essential for the results. With costly imitation we could interpret K as the difference between innovation and imitation costs.

this, the unit production cost of firm i is given by:

$$c_i(x_1, x_2) = \begin{cases} c - \gamma x_i & \text{for } x_1 = 1 \text{ and } x_2 = 1 \\ c - \gamma(x_i + \sigma x_j) & \text{else} \end{cases}, \quad i, j = 1, 2, i \neq j \tag{2}$$

where $c > \gamma$. The innovation activity analyzed in this paper is cost-reducing (process innovation). However, the results can be straightforwardly generalized to the case of product innovation.[3]

Total production costs are $C_i(x_1, x_2) = c_i(x_1, x_2) q_i$. The objective of firm i is to choose the R&D strategy that maximizes profits:

$$\Pi_i(x_1, x_2) = \pi_i(x_1, x_2) - Kx_i \tag{3}$$

where $\pi_i(x_1, x_2)$ denotes operating profits obtained in stage 2.

The solution concept is Subgame Perfect Nash Equilibrium (SPNE) and the game is solved by backward induction. First, for given R&D strategies the optimal equilibrium outputs are solved in the second stage. Then, firms' profit-maximizing R&D strategies in stage 1 are derived.

In *stage 2*, firm i chooses the output q_i in order to maximize its operating profit:

$$\pi_i = (a - bq_i - dq_j) q_i - c_i q_i, \ i, j = 1, 2, i \neq j. \tag{4}$$

From straightforward calculations we find that the Nash-Cournot equilibrium output for firm i is given by:

$$q_i = \frac{2b(a - c_i) - d(a - c_j)}{4b^2 - d^2}, \ i, j = 1, 2. \tag{5}$$

Notice, that the output of firm i is positive as long as $(a - c_i) > \frac{d}{2b}(a - c_j)$. Firm i's optimal equilibrium operating profit is given by $\pi_i = bq_i^2, \ i = 1, 2$.

In *stage 1*, firms choose their profit-maximizing R&D strategy. When both firms engage in R&D (i.e. $x_1 = x_2 = 1$), quantities and profits are:

$$q_i(1,1) = \frac{a - c + \gamma}{2b + d} \quad \text{and} \quad \Pi_i(1,1) = bq_i(1,1)^2 - K. \tag{6}$$

If none of the firms engages in R&D (i.e. $x_1 = x_2 = 0$), quantities and profits are equal to those of the classical Cournot model with differentiated products:

$$q_i(0,0) = \frac{a - c}{2b + d} \quad \text{and} \quad \Pi_i(0,0) = bq_i(0,0)^2. \tag{7}$$

[3] See Tishler and Milstein (2009) for this.

Finally, if one firm engages in R&D, say firm 1, and firm 2 decides to imitate, the corresponding quantities and profits are given by:[4]

$$q_1(1,0,\sigma) = \frac{(2b-d)(a-c)+(2b-d\sigma)\gamma}{4b^2-d^2} \quad \text{and} \quad \Pi_1(1,0,\sigma) = bq_1(1,0,\sigma)^2 - K \tag{8}$$

$$q_2(1,0,\sigma) = \frac{(2b-d)(a-c)+(2b\sigma-d)\gamma}{4b^2-d^2} \quad \text{and} \quad \Pi_2(1,0,\sigma) = bq_2(1,0,\sigma)^2. \tag{9}$$

The equilibrium R&D strategies are obtained as a result of each firm's best strategic response to the profit-maximizing strategy of the rival. The most interesting parameters that affect a firm's R&D strategy choice are the extent of spillovers in the industry and the degree of product differentiation, which sometimes is interpreted as a measure for the intensity of competition in the industry.[5]

The value of the spillover parameter reflects the legal and technical framework of the industry, specifically, the level of IPR protection or the ease of knowledge transfer in the market. The polar cases are a blue print diffusion in the absence of IPR protection, or the absolute ease of replication ($\sigma = 1$), and an absence of any knowledge diffusion when an invention can be completely protected by a patent, or a high level of knowledge sophistication that makes it impossible to replicate ($\sigma = 0$). In practice, most markets can be characterized by some intermediate level of spillovers. The degree of product differentiation varies from completely different products ($d = 0$) to homogeneous or identical products ($d = 1$). To exclude trivial cases we make restrictions on R&D costs:

Assumption 1. Let $\underline{K} < K < \overline{K}$ where $\underline{K}$ is defined by $\Pi_i(1,1) = \Pi_i(0,0)$, $i = 1,2$ and $\overline{K}$ is defined by $\Pi_2(1,1) = \Pi_2(1,0,0)$.

This assumption guarantees that costs are not too low such that making no R&D is a possible choice and that costs are not too high such that in the absence of spillovers firms are interested in investing in R&D. Thus, the focus of the analysis is to characterize the conditions under which engaging in or abstaining from own R&D is a non-trivial Nash equilibrium. Assuming that firm 1 decides to innovate, from expressions (6) and (9) we see that firm 2 faces a trade-off when choosing between innovation and imitation. On the one hand, if firm 2 decides to innovate it must pay a cost K, which in turn allows to obtain a reduction of unit production costs. On the other hand, if firm

[4] Further on, without loss of generality, we assume that firm 1 innovates and firm 2 imitates.

[5] Among others, this interpretation is used by Tishler and Milstein (2009). However, as discussed by Theilen (2012) and from the results of Vives (2008) this interpretation should be taken with some care.

2 decides to imitate, it saves the payment of the R&D cost K. Then, however, the decrease in unit production costs will be lower and depend on the R&D outcome of the innovator and the value of the spillover parameter.

To characterize the equilibria of the two-stage game, let $\underline{\sigma}$ be implicitly defined by $\Pi_i(1,1) - \Pi_2(1,0,\underline{\sigma}) = 0$ and $\overline{\sigma}$ by $\Pi_1(1,0,\overline{\sigma}) - \Pi_i(0,0) = 0$. We obtain the following proposition:

Proposition 1 *(Existence of equilibria)*

For given parameter values (d, b, a, c, γ) the equilibrium R&D strategies are characterized as follows:

(i) When spillovers are low ($\sigma \leq \underline{\sigma}$) there exists a pure strategy SPNE, in which both firms engage in R&D (Region I).

(ii) When spillovers are intermediate ($\underline{\sigma} \leq \sigma \leq \overline{\sigma}$) there exist multiple pure strategy SPNE, in which one firm engages in R&D and the other firm chooses to imitate (Region II).

(iii) When spillovers are high ($\overline{\sigma} \leq \sigma$) there exists a pure strategy SPNE, in which none of the firms engages in R&D (Region III).

Furthermore, $\partial\overline{\sigma}/\partial K < 0$, $\partial\underline{\sigma}/\partial K < 0$, $\partial\overline{\sigma}/\partial\gamma < 0$, $\partial\underline{\sigma}/\partial\gamma < 0$, $\partial\overline{\sigma}/\partial\,(a-c) > 0$ and $\partial\underline{\sigma}/\partial\,(a-c) > 0$.

The three regions are displayed in Figure 1. In Region I there exists a unique SPNE in pure strategies in which both firms innovate. This equilibrium is obtained when spillovers and R&D costs are low and when markets are large. Actually, Region I corresponds to the case of a highly innovative competitive industry with either an elevated level of knowledge protection or knowledge sophistication such that innovations are difficult to copy. In Region III there exists a unique SPNE in which none of the firms innovates though innovation would be individually profitable. This equilibrium emerges in the presence of high spillovers and elevated product homogeneity. Region III is an example of markets where competition together with free knowledge flows discourages innovation.

While firms' R&D strategies in Regions I and III are symmetric, in Region II both firms choose opposed strategies in equilibrium. Furthermore, we have multiple equilibria with one innovating and one imitating firm.[6] This is the case for intermediate spillover levels. An increase in R&D cost K and a decrease in market size $a - c$ shifts the curves to the "south-west" so that Region I becomes smaller and innovation in Region II holds for lower spillover level. Amir and Wooders (2000) also find that initially symmetric firms apply different R&D strategies in equilibrium and therefore perform asymmetrically. However, in our model this is not necessarily the case but depends on both the intensity of competition and the degree of IPR protection. We deal with the multiplicity of equilibria in Region II by assuming that either pure-strategy equilibrium is played with equal probability. The qualitative nature of the results does not depend on the selection of the equilibrium but reflects the initial symmetry between firms and their choices. So, if we allow for mixed strategy equilibria the comparison of payoffs and social welfare between regions remains the same.

Proposition 2 *(The effect of σ on aggregated output and social welfare)*

(i) Output and welfare are lower in the area of high spillovers (in Region III) than in the area of low spillovers (in Region I);

(ii) Output is increasing in σ and welfare is convex in σ for intermediate spillovers (in Region II);

(iii) Output decreases when passing from low to intermediate and from intermediate to high spillovers. Welfare can increase or decrease when passing from low to intermediate spillovers (from Region I to Region II) and welfare decreases when passing from intermediate to high spillovers (from Region II to Region III).

To illustrate the results of Proposition 2, we display the effect of changes in spillovers on aggregate industry output and welfare for some parameter values in Figure 2. We obtain two principal results. First, the relationship between the level of spillovers and aggregated industry output is non-monotonic. So, since the industry output is lower when spillovers are high, for intermediate spillover levels an increase of σ increases industry output. Second, a similar result holds for the relationship between the level of spillovers and social welfare with the difference that welfare might be even higher for an intermediate spillover level than for a low one.

[6] See also Zhou (2009) who assumes exogenously one innovating firm and n imitators and analyzes how competitive pressure affects the innovator's incentives to engage in R&D.

These results imply that the answer to the question of whether spillovers favor or discourage innovation is not straightforward. In our model spillovers have two different effects on the level of R&D output. A first effect is that with higher spillovers, in equilibrium, fewer firms are innovators. This decreases R&D output. A second effect is that with higher spillovers imitators obtain greater efficiency gains from the use of innovators' less costly technology. This increases aggregated industry output and social welfare. While the first effect tends to dominate if changes in spillover levels are large, the second effect dominates for small variations of σ. However, because of discontinuities, small changes in spillovers can also lead to important reductions in R&D output, aggregated industry output and social welfare. Therefore, a crucial question is to find the right level of spillovers. This result provides a possible explanation to the long and controversial discussion concerning the duration of patents.[7]

Regarding the effect of product differentiation on aggregated industry output and social welfare we find that when products are more homogenous firms need more IPR protection in order to maintain incentives for innovation. This finding is supported by empirical evidence for U.S. drug companies in the 1970s and 1980s. For this data, Shankar et al. (1998) show that the capacity to differentiate products acts as an important factor for firms' survival.

2.3 Extensions

2.3.1 Asymmetric firms

The results of Section 2 can be extended for the case of initially asymmetric firms where the inverse demand function of good i is:

$$p_i = a_i - bq_i - dq_j, \quad i, j = 1, 2, i \neq j, b - d \geq 0, \tag{10}$$

[7] Helpman (1993), Aghion et al. (2001), Bessen and Maskin (2009) and Zhou (2009), for example, argue against patents because of their redundant and excessive protection, which discourages firms' incentives for innovation. Halmenschlager (2006) and Fershtman and Markovich (2010) also find that the presence of patent protection on an intermediate stage would delay the pace of innovation and that lower spillovers are not the optimal public policy. Finally, Boldrin and Levine (2008) find that the greater the market scale (industry size) the more reduced should be IP protection. On the other hand, Arora and Gambardella (1994), Gans and Stern (2003), Gans et al. (2008) argue that IPR protection is essential for the existence of a market for technology.

and the unit production cost of firm i is given by:

$$c_i(x_i, x_j) = \begin{cases} c_i - \gamma x_i & \text{for } x_i = 1 \text{ and } x_j = 1 \\ c_i - \gamma(x_i + \sigma x_j) & \text{else} \end{cases}, \quad i, j = 1, 2, i \neq j. \tag{11}$$

Following Tishler and Milstein (2009), without loss of generality we assume that initially firm 1 is larger than firm 2, $a_1 - c_1 > a_2 - c_2$. Defining $M = (a_1 - c_1) + (a_2 - c_2)$, and $\epsilon = (a_1 - c_1)/M$, this means that $\epsilon \in \left(\frac{1}{2}, 1\right)$. The Nash-Cournot equilibrium output for firm i is given by:

$$q_i = \frac{2b(a_i - c_i) - d(a_j - c_j)}{4b^2 - d^2}, \; i, j = 1, 2. \tag{12}$$

Now, four possible situations may occur. When none of the firms innovates, firms' outputs are given by:

$$q_1(0,0) = \frac{2b\epsilon M - d(1-\epsilon)M}{4b^2 - d^2} \quad \text{and} \quad q_2(0,0) = \frac{2b(1-\epsilon)M - d\epsilon M}{4b^2 - d^2}. \tag{13}$$

The corresponding profits are $\Pi_1(0,0) = bq_1(0,0)^2$ and $\Pi_2(0,0) = bq_2(0,0)^2$. When both firms innovate, the output of each firm is:

$$q_1(1,1) = \frac{2b\epsilon M - d(1-\epsilon)M + (2b-d)\gamma}{4b^2 - d^2} \quad \text{and} \quad q_2(1,1) = \frac{2b(1-\epsilon)M - d\epsilon M + (2b-d)\gamma}{4b^2 - d^2}. \tag{14}$$

The corresponding profits are $\Pi_1(1,1) = bq_1(1,1)^2 - K$ and $\Pi_2(1,1) = bq_2(1,1)^2 - K$. When only firm 1 engages in R&D and firm 2 decides to imitate, the firms' outputs are:

$$q_1(1,0,\sigma) = \frac{2b\epsilon M - d(1-\epsilon)M + (2b - d\sigma)\gamma}{4b^2 - d^2} \quad \text{and} \quad q_2(1,0,\sigma) = \frac{2b(1-\epsilon)M - d\epsilon M + (2b\sigma - d)\gamma}{4b^2 - d^2}. \tag{15}$$

The firms' profits are $\Pi_1(1,0,\sigma) = bq_1(1,0,\sigma)^2 - K$ and $\Pi_2(1,0,\sigma) = bq_2(1,0,\sigma)^2$. Finally, if firm 2 engages in R&D and firm 1 decides to imitate, the firms' outputs are:

$$q_1(0,1,\sigma) = \frac{2b\epsilon M - d(1-\epsilon)M + (2b\sigma - d)\gamma}{4b^2 - d^2} \quad \text{and} \quad q_2(0,1,\sigma) = \frac{2b(1-\epsilon)M - d\epsilon M + (2b - d\sigma)\gamma}{4b^2 - d^2}. \tag{16}$$

The firms' profits are $\Pi_1(0,1,\sigma) = bq_1(0,1,\sigma)^2$ and $\Pi_2(0,1,\sigma) = bq_2(0,1,\sigma)^2 - K$.

Let $\underline{\sigma}_1$ be implicitly defined by $\Pi_1(1,1) = \Pi_1(1,0,\underline{\sigma}_1)$, $\overline{\sigma}_1$ by $\Pi_1(0,0) = \Pi_1(1,0,\overline{\sigma}_1)$, $\underline{\sigma}_2$ by $\Pi_2(1,1) = \Pi_2(1,0,\underline{\sigma}_2)$ and $\overline{\sigma}_2$ by $\Pi_2(0,0) = \Pi_2(1,0,\overline{\sigma}_2)$. Then, we obtain the following result:

Proposition 3 *(Existence of equilibria with asymmetric firms)*

Compared to the case of symmetric firms:

(i) The regions, in which both firms innovate or none of them innovates (Regions I and III) become smaller when firms are asymmetric, as for given values of d we have $\underline{\sigma}_2 < \underline{\sigma}$ and $\overline{\sigma}_1 > \overline{\sigma}$.

(ii) The region with multiple equilibria in which one of the firms innovates and the other imitates (Region II) becomes smaller, as for given d we have $\underline{\sigma}_1 > \underline{\sigma}$ and $\overline{\sigma}_2 < \overline{\sigma}$.

(iii) A new region with a unique pure strategy SPNE emerges (Region IV). In this region the large firm is an innovator and the small firm an imitator.

The four regions with the resulting equilibria are displayed in Figure 3. A specific feature of this extension is that allowing for initially asymmetric firms leads to the emergence of an area where the larger firm is an innovator and the smaller firm chooses to imitate. Thus, an increase in a firm's relative dominance raises incentives for that firm to innovate and decreases those of the rival. Empirical evidence widely supports this result. For instance, Henderson and Cockburn (1996) using data from individual research programs of pharmaceutical firms in the United States, suggest the advantage of large firms in the conduct of basic research.

The difference between the situations in Region II and Region IV can be explained in terms of the persistence of firms' R&D strategies. In Region II we have equilibria where the optimal strategy of a firm is opposed to that of the rival. If the rival innovates the best reply is to imitate, and vice versa. Therefore, in a repeated context of this game, firms will not follow a continuous innovation strategy in Region II. On the contrary, in Region IV initially asymmetric firms always choose the same R&D strategy. The larger firm innovates and the smaller firm imitates. So, in Region IV, both firms continuously choose the same R&D strategy. The results in Proposition 3 allow us to obtain testable predictions of how market conditions such as product differentiation, firm asymmetries and spillovers affect firm's R&D strategy choice.

Proposition 4 *(The effect of ϵ, firm asymmetry, on aggregated output and social welfare)*

(i) Aggregated industry output is constant in ϵ in all regions, where $q(0,0) < q(1,0,\sigma) = q(0,1,\sigma) < q(1,1)$.

(ii) When changes in ϵ do not yield changes in firms' R&D strategies, in all region there exists at least one equilibrium in which social welfare is increasing in ϵ.

(iii) When changes in ϵ yield changes in firms' R&D strategies, social welfare decreases when the number of innovators decreases.

Endogenizing a firm's decision to innovate or to abstain from innovation we obtain that asymmetries between firms, which may lead to a persistent innovator-imitator configuration in the market, can have both a positive and a negative effect on social welfare. A positive effect on welfare is obtained when greater dominance does not affect a firms' R&D decision. Then, the output increase of the dominant firm more than compensates the output loss by the smaller firm.[8] Furthermore, a positive effect on social welfare is also obtained when market dominance means that the larger firm becomes an innovator. However, when more market dominance causes the smaller firm to abstain from innovation, the welfare effect is negative. This happens when products are highly differentiated and spillovers are low. Therefore, in situations in which firms are already protected against competitors market dominance is bad. We conclude that dominance is good for innovation when property rights are weak (spillovers are large) and competition is high but discourages innovation when the IPR protection is large and competition is weak.

2.3.2 n firms

In this section we analyze how the results extend to oligopoly markets with n initially symmetric firms. In this case, the corresponding inverse demand function of good i is given by:

$$p_i = a - bq_i - d\sum_{j\neq i} q_j,\ i = 1, ..., n, \tag{17}$$

We assume that spillovers occur when at least one firm decides to innovate. Thus, unit production cost are:

$$c_i\left(x_i, x_{-i}\right) = \begin{cases} c-\gamma & \text{if } x_i = 1 \\ c-\gamma\sigma & \text{if } x_i = 0 \text{ and } \exists j \text{ with } x_j = 1 \\ c & \text{else} \end{cases},\ i = 1, ..., n. \tag{18}$$

In *stage 2*, firm i chooses the output q_i to maximize its operating profit:

$$\pi_i = \left(a - bq_i - d\sum_{j\neq i} q_j\right) q_i - c_i q_i,\ i, j = 1, 2, i \neq j. \tag{19}$$

[8] This result is similar to Tishler and Milstein (2009). For example, with $d = 0$ it means that it is better to have one monopolist in one large market than to have two monopolists in two small markets.

The Nash-Cournot equilibrium output for firm i is given by:

$$q_i = \frac{(2b-d)(a-c_i) - d\left(nc_i - \sum_{j=1}^{n} c_j\right)}{(2b-d)(2b+d(n-1))}. \tag{20}$$

In *stage 1*, firms choose their profit-maximizing R&D strategy. When all firms engage in R&D (i.e. $x_1 = ... = x_n = 1$), outputs and profits are:

$$q_i(1,...,1) = \frac{a-c+\gamma}{2b+d(n-1)} \quad \text{and} \quad \Pi_i(1,...,1) = bq_i(1,...,1)^2 - K. \tag{21}$$

If none of the firms engages in R&D (i.e. $x_1 = ... = x_n = 0$), output and profits are equal to those of the classical Cournot model with differentiated products:

$$q_i(0,...,0) = \frac{a-c}{2b-d+dn} \quad \text{and} \quad \Pi_i(0,...,0) = bq_i(0,...,0)^2. \tag{22}$$

Furthermore, if all firms except one, say firm 1, engage in R&D the corresponding output and profit of firm 1 are given by:

$$q_1(0,1,...,1,\sigma) = \frac{(2b-d)(a-c+\sigma\gamma) - (n-1)(1-\sigma)\gamma d}{(2b-d)(2b+d(n-1))} \quad \text{and} \quad \Pi_1(0,1,...,1,\sigma) = bq_1(0,1,...,1,\sigma)^2. \tag{23}$$

Finally, if none of the firms innovates, except one, say firm 1, the corresponding output and profit of firm 1 are given by:

$$q_1(1,0,...0,\sigma) = \frac{(2b-d)(a-c+\gamma) + (n-1)(1-\sigma)\gamma d}{(2b-d)(2b+d(n-1))} \quad \text{and} \quad \Pi_1(1,0,...0,\sigma) = bq_1(1,0,...0,\sigma)^2 - K. \tag{24}$$

To analyze how the frontiers of Region I and Region III depend on the number of firms in the market, we examine a firm's choice between innovation and imitation. First, we assume that all other firms in the industry innovate. Second, we assume that all other firms do not engage in R&D. Let $\underline{\sigma}_n$ be such that $\Pi_i(1,1,..,1) = \Pi_1(0,1,...,1,\underline{\sigma}_n)$ and $\overline{\sigma}_n$ such that $\Pi_1(1,0,..,0,\overline{\sigma}_n) = \Pi_i(0,0,..,0)$.

Proposition 5 *(The effect of* n*, competitive pressure, on equilibria)*

Compared to the duopoly case with two symmetric firms we have:

(i) The region, in which all firms innovate (Region I) decreases with the number of firms in the market as for given d we have $\underline{\sigma}_n < \underline{\sigma}_{n-1}$.

(ii) The region, in which none of the firms innovates (Region III) increases with the number of firms in the market as for given d we have $\overline{\sigma}_n < \overline{\sigma}_{n-1}$.

Figure 4 displays how Regions I and III change when the number of firms in the market increases. Regarding Region I, we observe that the probability of a particular firm to engage in R&D decreases as the number of competitors increases. With more competitors initially symmetric firms will be innovators only when products are sufficiently differentiated and IPR protection is high. This finding is supported by empirical evidence from Shankar et al. (1998). Though Region I shirks with entry, notice that the overall innovative performance in the market increases within Region I as entrants also engage in R&D. With more competitors what was formerly Region II becomes more complex as further possible equilibria emerge. For example, with three firms we can have multiple equilibria with one innovator and two imitators or with two innovators and one imitator. Concerning Region III, we find that the entry of new firms means that equilibria with no innovating firm will occur for lower spillover values and for more differentiated products. Together, these results imply that the effect of entry on total R&D performance and welfare depends on spillovers and product differentiation. Concretely, we get the following result.

Proposition 6 *(The effect of* n*, competitive pressure, on industry R&D output and welfare)*

(i) Entry increases (decreases) total R&D output and welfare when spillovers are low and products are highly differentiated (spillovers are high and products are rather homogenous).

(ii) For given parameter values of (d, σ) an increase in n can first increase R&D output and welfare and then decrease it.

The first result highlights the role of both, IPR protection and the degree of product differentiation to assess the effect of changes in competition. Generally, we can say that more competition is good in markets with highly differentiated products and when IPR protection is high. On the contrary, increased competition is bad when products are homogeneous and IPR protection is weak. The second result indicates how changes in competitive pressure (the number of firms in the market) affect innovative effort. Notice, that with entry we can have more innovators. However, the (d,σ)-spaces in which all firms innovate and in which no firm innovates increase with entry. For example, from Figure

4 we see for $(d, \sigma) = (0.15, 0.1)$ that when the number of firms in the market passes from 3 to 5 to 10, total innovative effort passes from 3 to 5 to 0. So, as in the Aghion et al. (2005) growth model we find an inverted U-shaped relationship between innovative effort and competitive pressure. However, for higher values of σ, from the beginning, entry can yield to a decline of innovative effort and welfare, a result also found in Tishler and Milstein (2009) or De Bondt et al. (1992) because with high spillovers more rivals lead to reduced investments, output and profitability and reduced social welfare. As a general result we find that the effect of changes in competitive pressure measured by the number of firms, again, depends on both IPR protection and the degree of product differentiation.

2.4 Concluding remarks

This paper analyzes how the equilibrium R&D strategies of firms are affected by external factors such as spillovers and competitive pressure. The analysis contributes to the understanding of a firm's R&D strategy choice. In this paper, especially, we focus on a firms' choice to innovate or to imitate. From the model we obtain that when firms choose endogenously their optimal R&D strategies three types of equilibria arise: equilibria in which all firms innovate, equilibria in which firms choose asymmetric R&D strategies with one innovating and one imitating firm, and, finally, equilibria in which no firm innovates. We find that stronger intellectual property rights protection provides higher incentives for firms to engage in R&D. Nevertheless, smaller firms are less likely to be innovators in markets with homogenous product and high levels of spillovers. The welfare consequences of having a dominate firm can be positive or negative. This depends on whether market dominance discourages smaller firms to innovate. An increase in the number of competitors can first increase innovative effort and welfare but then decrease them. So, our model would explain an inverted U-shaped relationship between innovative effort and competitive pressure. However, this relationship will depend on both the degree of product differentiation and IPR protection. Regarding social welfare, if a market is characterized by a high rate of innovation a reduction of IPR protection can discourage innovative performance and welfare substantially. However, a reduction of IPR protection can also increase social welfare because it may induce imitation resulting in higher aggregate industry output. The future research should apply the dynamic framework to the analysis of firm R&D strategy choice.

Some important policy implications are obtained from our results. We find that a common IPR protection policy irrespective specific market and firms characteristics is inappropriate. The analysis of spillover effects on social welfare shows that a reduction of IPR protection can discourage innovative performance but also allow for imitation with a positive total welfare effect. Another implication of our findings is that the IPR protection policy must be tightly coordinated with the competition policy because external parameters such as IPR protection and competitive pressure jointly affect the firms' R&D strategy choice. Naturally, the implementation of such a policy is not an easy task because sectors might not be easily identified or firms and patents might not be easily assigned to a specific sector. However, because the welfare gains from sector specific R&D policies might be substantial, future research should help us to identify these sectors and to indicate the appropriate R&D policy for them.

Despite the equal patent length independently on the sector, the royalties regulation can be considered as an example of a feasible sector-specific IP protection policy. In the sectors with substantial market power the maximum royalties should be set based on the incremental value that the patented technology adds to the product. Thus, it decreases the intellectual monopoly of innovators. It is especially important in industries where technologies get obsolete at a high pace (for instance, electrical equipment, ICT, etc.). In such indutries the increase in imitation, induced by decreased intellectual monopoly can be growth enhancing.

2.5 Appendix.

2.5.1 Proof of Proposition 1

Define $\overline{\sigma}$ such that firm i is indifferent between engaging and abstaining from R&D when firm j imitates:

$$\Pi_1(1,0,\overline{\sigma}) - \Pi_i(0,0) = b\left(\frac{2b\,(a-c+\gamma) - d\,(a-c+\overline{\sigma}\gamma)}{4b^2-d^2}\right)^2 - K - b\left(\frac{2b\,(a-c) - d\,(a-c)}{4b^2-d^2}\right)^2 = 0, \tag{25}$$

that is:

$$\overline{\sigma} = \frac{2b\,(a-c+\gamma) - d\,(a-c)}{d\gamma} - \frac{\left(4b^2-d^2\right)}{d\gamma}\sqrt{\frac{K}{b} + \left(\frac{a-c}{2b+d}\right)^2}. \tag{26}$$

Define $\underline{\sigma}$ such that firm i is indifferent between engaging and abstaining from R&D when firm j

engages in R&D:

$$\Pi_i(1,1)-\Pi_2(1,0,\underline{\sigma}) = b\left(\frac{2b\left(a-c+\gamma\right)-d\left(a-c+\gamma\right)}{4b^2-d^2}\right)^2 - K - b\left(\frac{2b\left(a-c+\underline{\sigma}\gamma\right)-d\left(a-c+\gamma\right)}{4b^2-d^2}\right)^2 = 0 \tag{27}$$

that is:

$$\underline{\sigma} = \frac{-2b\left(a-c\right)+d\left(a-c+\gamma\right)}{2b\gamma} + \frac{\left(4b^2-d^2\right)}{2b\gamma}\sqrt{\left(\frac{a-c+\gamma}{2b+d}\right)^2 - \frac{K}{b}} \tag{28}$$

First, consider the partial derivatives. From equations (26) and (28) we have: $\partial\overline{\sigma}/\partial K < 0$, $\partial\underline{\sigma}/\partial K < 0$, $\partial\overline{\sigma}/\partial\gamma = -\overline{\sigma}/\gamma < 0$, $\partial\underline{\sigma}/\partial\gamma = -\ \underline{\sigma}/\gamma < 0$,

$$\partial\overline{\sigma}/\partial\left(a-c\right) = \frac{2b-d}{d\gamma}\left[1-\left(\frac{a-c}{2b+d}\right)\left(\frac{K}{b}+\left(\frac{a-c}{2b+d}\right)^2\right)^{-1/2}\right] > 0, \text{ and} \tag{29}$$

$$\partial\underline{\sigma}/\partial\left(a-c\right) = -\frac{2b-d}{2b\gamma}\left[1-\left(\frac{a-c+\gamma}{2b+d}\right)\left(\left(\frac{a-c+\gamma}{2b+d}\right)^2-\frac{K}{b}\right)^{-1/2}\right] > 0. \tag{30}$$

To prove existence of the equilibria we make the following claims:

Claim 1: $\overline{\sigma} > \underline{\sigma}$.

We have:

$$\overline{\sigma}-\underline{\sigma} = \frac{\left(4b^2-d^2\right)}{\gamma d}\left(\frac{\left(a-c+\gamma\right)}{2b} - \sqrt{\frac{K}{b}+\left(\frac{a-c}{2b+d}\right)^2} - \frac{d}{2b}\sqrt{\left(\frac{a-c+\gamma}{2b+d}\right)^2-\frac{K}{b}}\right) \tag{31}$$

This is an increasing function in K under assumption 1, i.e.

$$\partial\frac{\overline{\sigma}-\underline{\sigma}}{\partial K} = \frac{\left(4b^2-d^2\right)}{2b\gamma d}\left(-\left(\frac{K}{b}+\left(\frac{a-c}{2b+d}\right)^2\right)^{-\frac{1}{2}} + \frac{d}{2b}\left(\left(\frac{a-c+\gamma}{2b+d}\right)^2-\frac{K}{b}\right)^{-\frac{1}{2}}\right) > 0 \tag{32}$$

for $K > \underline{K}$. Therefore, a sufficient condition for $\overline{\sigma} > \underline{\sigma}$ is that the condition holds for $K = \underline{K}$:

$$\begin{aligned}\overline{\sigma}-\underline{\sigma} &= \frac{\left(4b^2-d^2\right)}{\gamma d}\left(\frac{\left(a-c+\gamma\right)}{2b} - \sqrt{\frac{\underline{K}}{b}+\left(\frac{a-c}{2b+d}\right)^2} - \frac{d}{2b}\sqrt{\left(\frac{a-c+\gamma}{2b+d}\right)^2-\frac{\underline{K}}{b}}\right) \\ &= \frac{1}{2b}\left(2b-d\right) > 0.\end{aligned} \tag{33}$$

Claim 2: $\overline{\sigma} < 1$.

From assumption 1 we have that $K > \underline{K} = b\left(\frac{a-c+\gamma}{2b+d}\right)^2 - b\left(\frac{a-c}{2b+d}\right)^2$. Thus

$$\overline{\sigma} < \frac{2b\left(a-c+\gamma\right)-d\left(a-c\right)}{d\gamma} - \frac{\left(4b^2-d^2\right)}{d\gamma}\sqrt{\frac{\underline{K}}{b}+\left(\frac{a-c}{2b+d}\right)^2} = 1 \tag{34}$$

Claim 3: $\underline{\sigma} > 0$.

From assumption 1 we have $K < \overline{K} = b\left(\frac{a-c+\gamma}{2b+d}\right)^2 - b\left(\frac{(2b-d)(a-c)-d\gamma}{4b^2-d^2}\right)^2$. Thus, $\underline{\sigma} > \frac{-2b(a-c)+d(a-c+\gamma)}{2b\gamma} + \frac{(4b^2-d^2)}{2b\gamma}\sqrt{\left(\frac{a-c+\gamma}{2b+d}\right)^2 - \frac{\overline{K}}{b}} = 0$.

Together, claims 1-3 prove the existence of the different equilibria.

2.5.2 Proof of Proposition 2

First, consider aggregated output. We have:

$$q(1,1) = \frac{2(a-c+\gamma)}{2b+d} > q(1,0,\sigma) = \frac{2(a-c)+(1+\sigma)\gamma}{2b+d} > q(0,0) = \frac{2(a-c)}{2b+d} \tag{35}$$

and $\partial q(1,0,\sigma)/\partial\sigma > 0$ which proves the statements regarding aggregated output.

Next, consider social welfare. When both firms engage in R&D, (i.e. $x_i = 1, \ \ i = 1,2$) social welfare is:

$$W(1,1) = (3b+d)\left(\frac{a-c+\gamma}{2b+d}\right)^2 - 2K \tag{36}$$

If none of the firms engages in R&D, (i.e. $x_i = 0, \ \ i = 1,2$) social welfare is:

$$W(0,0) = (3b+d)\left(\frac{a-c}{2b+d}\right)^2 \tag{37}$$

Finally, if firm 1 engages in R&D and firm 2 decides to imitate, social welfare is:

$$\begin{aligned} W(1,0,\sigma) &= \Pi_1(1,0,\sigma) + \Pi_2(0,1,\sigma) + dq_1(1,0,\sigma)q_2(0,1,\sigma) + \frac{1}{2}b\left(q_1^2(1,0,\sigma) + q_2^2(0,1,\sigma)\right) \\ &= \frac{3}{2}b\left(\frac{a-c}{2b+d} + \frac{(2b-d\sigma)\gamma}{4b^2-d^2}\right)^2 + \frac{3}{2}b\left(\frac{a-c}{2b+d} + \frac{(2b\sigma-d)\gamma}{4b^2-d^2}\right)^2 \\ &\quad + d\left(\frac{a-c}{2b+d} + \frac{(2b-d\sigma)\gamma}{4b^2-d^2}\right)\left(\frac{a-c}{2b+d} + \frac{(2b\sigma-d)\gamma}{4b^2-d^2}\right) - K \end{aligned} \tag{38}$$

To prove statement (i), from (36) and (37) we have:

$$\begin{aligned} W(1,1) - W(0,0) &= (2b+d)^{-2}(2a-2c+\gamma)(3b+d)\gamma - 2K \\ &> (2b+d)^{-2}(2a-2c+\gamma)(3b+d)\gamma - 2\overline{K} \\ &= \frac{2(b-d)(4b^2-d^2)(a-c) + (4b^3-bd^2+d^3)\gamma}{(4b^2-d^2)^2}\gamma > 0 \end{aligned} \tag{39}$$

To prove statement (ii), consider the second derivative of (38):

$$\frac{\partial^2 W(1,0,\sigma)}{\partial \sigma^2} = \frac{\left(12b^2 - d^2\right) b\gamma^2}{\left(4b^2 - d^2\right)^2} > 0. \tag{40}$$

Finally, to prove statement (iii), we analyze when

$$W(1,0,\underline{\sigma}) < W(1,1). \tag{41}$$

By definition of $\underline{\sigma}$ we have $\Pi_2(0,1,\underline{\sigma}) = \Pi_2(1,1)$. So, (41) is equivalent to

$$\Pi_1(1,0,\underline{\sigma}) + dq_1(1,0,\underline{\sigma})q_2(0,1,\underline{\sigma}) + \frac{1}{2}b\left(q_1^2(1,0,\underline{\sigma}) + q_2^2(0,1,\underline{\sigma})\right) < \Pi_1(1,1) + (d+b)\, q_1(1,1)q_2(1,1) \tag{42}$$

or

$$\frac{1}{2}\gamma\left(\underline{\sigma} - 1\right)\left(2\left(b-d\right)\left(a-c\right) + \gamma\left(b - 2d + b\underline{\sigma}\right)\right) < 0 \tag{43}$$

or

$$\frac{1}{4}\gamma\left(\underline{\sigma} - 1\right)\left(\left(2b-3d\right)\left(a-c+\gamma\right) + \left(4b^2-d^2\right)\sqrt{\left(\frac{a-c+\gamma}{2b+d}\right)^2 - \frac{K}{b}}\right) < 0. \tag{44}$$

This is true if $2b > 3d$ or $K < \frac{8(b-d)(a-c+\gamma)^2 bd}{(4b^2-d^2)^2}$. Notice, that in case of homogeneous products the conditions are not fulfilled such that $W(1,0,\underline{\sigma}) > W(1,1)$.

Next, we analyze when

$$W(1,0,\overline{\sigma}) > W(0,0). \tag{45}$$

By definition of $\overline{\sigma}$ we have $\Pi_1(1,0,\overline{\sigma}) = \Pi_1(0,0)$. So (45) is equivalent to

$$\Pi_2(0,1,\overline{\sigma}) + dq_1(1,0,\overline{\sigma})q_2(0,1,\overline{\sigma}) + \frac{1}{2}b\left(q_1^2(1,0,\overline{\sigma}) + q_2^2(0,1,\overline{\sigma})\right) > \Pi_2(0,0) + (d+b)\, q_1^2(0,0) \tag{46}$$

orϵ

$$2\left(a-c\right)\left(b-d+\left(3b-d\right)\underline{\sigma}\right) + \gamma\left(b + 3b\sigma^2 - 2d\underline{\sigma}\right) > 0 \tag{47}$$

which always holds.

2.5.3 Proof of Proposition 3

From the definition of $\underline{\sigma}_1$, $\overline{\sigma}_1$, $\underline{\sigma}_2$ and $\overline{\sigma}_2$ we obtain:

$$\underline{\sigma}_1 = -\frac{2b\epsilon M - d(1-\epsilon)M - d\gamma}{2b\gamma} + \frac{4b^2-d^2}{2b\gamma}\sqrt{\frac{(2b\epsilon M - d(1-\epsilon)M + \gamma(2b-d))^2}{(4b^2-d^2)^2} - \frac{K}{b}} \tag{48}$$

$$\overline{\sigma}_1 = \frac{2b(M\epsilon+\gamma) - Md(1-\epsilon)}{d\gamma} - \frac{(4b^2-d^2)}{d\gamma}\sqrt{\frac{K}{b} + \frac{(2b\epsilon M - d(1-\epsilon)M)^2}{(4b^2-d^2)^2}} \tag{49}$$

$$\underline{\sigma}_2 = -\frac{2b(1-\epsilon)M - d(\epsilon M+\gamma)}{2b\gamma} + \frac{(4b^2-d^2)}{2b\gamma}\sqrt{\frac{(2b(1-\epsilon)M - d\epsilon M + \gamma(2b-d))^2}{(4b^2-d^2)^2} - \frac{K}{b}} \tag{50}$$

$$\overline{\sigma}_2 = \frac{2b(1-\epsilon)M - d\epsilon M + 2b\gamma}{d\gamma} - \frac{4b^2-d^2}{d\gamma}\sqrt{\left(\frac{2b(1-\epsilon)M - d\epsilon M}{4b^2-d^2}\right)^2 + \frac{K}{b}} \tag{51}$$

Because $\epsilon \in \left(\frac{1}{2}, 1\right)$, statement (i) is true if

$$\frac{\partial \underline{\sigma}_2}{\partial \epsilon} = \frac{(2b+d)M}{2b\gamma}\left(1 - \frac{\frac{(2b(1-\epsilon)M - d\epsilon M + \gamma(2b-d))}{(4b^2-d^2)}}{\sqrt{\frac{(2b(1-\epsilon)M - d\epsilon M + \gamma(2b-d))^2}{(4b^2-d^2)^2} - \frac{K}{b}}}\right) < 0 \text{ and} \tag{52}$$

$$\frac{\partial \overline{\sigma}_1}{\partial \epsilon} = \frac{(2b+d)M}{d\gamma}\left(1 - \frac{\frac{(2b\epsilon M - d(1-\epsilon)M)}{(4b^2-d^2)}}{\sqrt{\frac{K}{b} + \frac{(2b\epsilon M - d(1-\epsilon)M)^2}{(4b^2-d^2)^2}}}\right) > 0 \tag{53}$$

which holds if $K > 0$.

Similarly, statement (ii) is true if

$$\frac{\partial \underline{\sigma}_1}{\partial \epsilon} = \frac{(2b+d)M}{2b\gamma}\left(-1 + \frac{\frac{2(2b\epsilon M - d(1-\epsilon)M + \gamma(2b-d))}{(4b^2-d^2)}}{\sqrt{\frac{(2b\epsilon M - d(1-\epsilon)M + \gamma(2b-d))^2}{(4b^2-d^2)^2} - \frac{K}{b}}}\right) > 0 \text{ and} \tag{54}$$

$$\frac{\partial \overline{\sigma}_2}{\partial \epsilon} = \frac{(2b+d)M}{d\gamma}\left(-1 + \frac{\frac{2(2b(1-\epsilon)M - d\epsilon M)}{(4b^2-d^2)}}{\sqrt{\left(\frac{2b(1-\epsilon)M - d\epsilon M}{4b^2-d^2}\right)^2 + \frac{K}{b}}}\right) < 0 \tag{55}$$

which also holds if $K > 0$.

Finally, statement (iii) follows directly from the former two. When all regions shrink, a new region must emerge. The characteristics of the equilibrium in this region follow from the definition of the regions' frontiers.

2.5.4 Proof of Proposition 4

Statement (i) follows immediately from:

$$q(0,0) = \frac{M}{2b+d} < q(1,0,\sigma) = q(0,1,\sigma) = \frac{M+(1+\sigma)\gamma}{2b+d} < q(1,1) = \frac{M+2\gamma}{2b+d} \tag{56}$$

which are all independent from ϵ.

To prove statement (ii), consider the social welfare in the different regions:

$$W(0,0) = \frac{\left(12b^2-d^2\right)b - 2\epsilon\left(1-\epsilon\right)\left(3b-d\right)\left(2b+d\right)^2}{2\left(4b^2-d^2\right)^2} M^2 \tag{57}$$

$$W(1,1) = \frac{2\gamma\left(3b+d\right)\left(2b-d\right)^2\left(M+\gamma\right) + \left(\left(12b^2-d^2\right)b - 2\epsilon\left(1-\epsilon\right)\left(3b-d\right)\left(2b+d\right)^2\right)M^2}{2\left(4b^2-d^2\right)^2} - 2K \tag{58}$$

$$W(1,0,\sigma) = \frac{3}{2}b\left(\frac{2b\epsilon M - d\left(1-\epsilon\right)M + \left(2b-d\sigma\right)\gamma}{4b^2-d^2}\right)^2 + \frac{3}{2}b\left(\frac{2b\left(1-\epsilon\right)M - d\epsilon M + \left(2b\sigma-d\right)\gamma}{4b^2-d^2}\right)^2$$
$$+d\frac{2b\epsilon M - d\left(1-\epsilon\right)M + \left(2b-d\sigma\right)\gamma}{4b^2-d^2}\frac{2b\left(1-\epsilon\right)M - d\epsilon M + \left(2b\sigma-d\right)\gamma}{4b^2-d^2} - K \tag{59}$$

$$W(0,1,\sigma) = \frac{3}{2}b\left(\frac{2b\epsilon M - d\left(1-\epsilon\right)M + \left(2b\sigma-d\right)\gamma}{4b^2-d^2}\right)^2 + \frac{3}{2}b\left(\frac{2b\left(1-\epsilon\right)M - d\epsilon M + \left(2b-d\sigma\right)\gamma}{4b^2-d^2}\right)^2$$
$$+d\frac{2b\epsilon M - d\left(1-\epsilon\right)M + \left(2b\sigma-d\right)\gamma}{4b^2-d^2}\frac{2b\left(1-\epsilon\right)M - d\epsilon M + \left(2b-d\sigma\right)\gamma}{4b^2-d^2} - K \tag{60}$$

Differentiation with respect to ϵ yields:

$$\frac{\partial W(0,0)}{\partial \epsilon} = \frac{\partial W(1,1)}{\partial \epsilon} = \frac{\left(2\epsilon-1\right)\left(3b-d\right)\left(2b+d\right)^2}{\left(4b^2-d^2\right)^2}M^2 \geq 0 \tag{61}$$

$$\frac{\partial W(1,0,\sigma)}{\partial \epsilon} = \frac{\left(\left(2\epsilon-1\right)M + \gamma\left(1-\sigma\right)\right)\left(3b-d\right)M}{\left(2b-d\right)^2} \geq 0 \tag{62}$$

for $\epsilon \in \left(\frac{1}{2}, 1\right)$. This guarantees that social welfare increases with ϵ in Regions I, III and IV in which we have a unique equilibrium. Furthermore, the last expression is sufficient to guarantee that there is at least one equilibrium in Region II in which social welfare increases with ϵ. This happens when the large firm is the innovator and the small firm the imitator. In the opposite case, in which the small firm is the innovator and the large firm the imitator we get

$$\frac{\partial W(0,1,\sigma)}{\partial \epsilon} = \frac{\left(\left(2\epsilon-1\right)M - \gamma\left(1-\sigma\right)\right)}{\left(2b-d\right)^2}\left(3b-d\right)M. \tag{63}$$

Then, social welfare does not necessarily increase with ϵ.

To prove statement (iii), from Proposition 3 we know that a change in ϵ increases region IV. This can yield three changes in the firms' equilibrium R&D strategies. First, instead of two innovators we can have one innovator and one imitator. Notice that social welfare can be written as

$$W = \frac{3}{2} b \left[(q - q_2)^2 + q_2^2 \right] + d (q - q_2) q_2, \tag{64}$$

where $\partial W / \partial q > 0$ and $\partial W / \partial q_2 = -(3b - d)(q - 2q_2) < 0$ for $q_2 < q_1 = q - q_2$. Therefore, $q(1,1) > q(1,0,\sigma)$, $q_2(1,1) - q_2(1,0,\sigma) = 2b\gamma (1 - \sigma) / \left(4b^2 - d^2\right) > 0$, $q_2(1,1) < q_1(1,1)$ and $q_2(1,0,\sigma) < q_1(1,0,\sigma)$ means that $W(1,1) - W(1,0,\sigma) > 0$, i.e. welfare is larger when both firms innovate than when firm 1 innovates and firm 2 imitates. Second, instead of a small innovator and a large imitator we can have a large innovator and a small imitator. Then we have:

$$W(1,0,\sigma) - W(0,1,\sigma) = M\gamma (2\epsilon - 1)(1 - \sigma) \frac{3b - d}{(2b - d)^2} > 0 \tag{65}$$

Finally, we can pass from a situation with no innovator to one with a large innovator and a small imitator. Notice that social welfare can be written as

$$W = \frac{3}{2} b \left[q_1^2 + (q - q_1)^2 \right] + d q_1 (q - q_1), \tag{66}$$

where $\partial W / \partial q > 0$ and $\partial W / \partial q_1 = -(3b - d)(q - 2q_1) > 0$ for $q_1 > q_2 = q - q_1$. Therefore, $q(0,0) < q(1,0,\sigma)$, $q_1(0,0) - q_1(1,0,\sigma) = -(2b - d\sigma)\gamma / \left(4b^2 - d^2\right) < 0$, $q_1(0,0) > q_2(0,0)$ and $q_1(1,0,\sigma) > q_2(1,0,\sigma)$ means that $W(1,0,\sigma) - W(0,0) > 0$, i.e. welfare is larger when firm 1 innovates and firm 2 imitates than when no firm innovates.

2.5.5 Proof of Proposition 5

To prove statement (i), from the definition of $\underline{\sigma}_n$ by $\Pi_i(1,...,1) - \Pi_1(0,1,...,1,\underline{\sigma}_n) = 0$ we get:

$$\begin{aligned} \underline{\sigma}_n &= \frac{-(2b - d)(a - c) + (n - 1)\gamma d}{\gamma (2b - 2d + dn)} + \frac{(2b - d)(2b + d(n - 1))}{\gamma (2b - 2d + dn)} \sqrt{\left(\frac{a - c + \gamma}{2b - d + dn}\right)^2 - \frac{K}{b}} \\ &= \frac{-(2b - d)(a - c + \gamma)}{\gamma (2b - 2d + dn)} + 1 + \left(\frac{(2b - d)}{\gamma} + \frac{(2b - d) d}{\gamma (2b - 2d + dn)}\right) \sqrt{\left(\frac{a - c + \gamma}{2b - d + dn}\right)^2 - \frac{K}{b}} \end{aligned} \tag{67}$$

From differentiation we get:

$$\begin{aligned} \frac{\partial \underline{\sigma}_n}{\partial n} &= \frac{d (2b - d)(a - c + \gamma)}{\gamma (2b - 2d + dn)^2} - d \left(\frac{(2b - d) d}{\gamma (2b - 2d + dn)^2}\right) \sqrt{\left(\frac{a - c + \gamma}{2b - d + dn}\right)^2 - \frac{K}{b}} \\ &\quad - d \left(\frac{(2b - d)}{\gamma} + \frac{(2b - d) d}{\gamma (2b - 2d + dn)}\right) \left(\left(\frac{a - c + \gamma}{2b - d + dn}\right)^2 - \frac{K}{b}\right)^{-\frac{1}{2}} \left(\frac{a - c + \gamma}{2b - d + dn}\right)^2 (2b - d + dn)^{-1} \\ &< 0 \end{aligned} \tag{68}$$

iff

$$\frac{K}{b}+\frac{(2b-3d+dn)(a-c+\gamma)^2}{(2b-d+dn)d^2}>0 \tag{69}$$

which always holds.

To prove statement (ii), from the definition of $\overline{\sigma}_n$ by $\Pi_1(1,0,..,0,\overline{\sigma}_n)-\Pi_i(0,0,..,0)=0$ we get:

$$\overline{\sigma}_n=1+\frac{(2b-d)(a-c+\gamma)}{(n-1)\gamma d}-\frac{(2b-d)(2b+d(n-1))}{(n-1)\gamma d}\sqrt{\left(\frac{a-c}{2b-d+dn}\right)^2+\frac{K}{b}} \tag{70}$$

From differentiation we get:

$$\begin{aligned}\frac{\partial\overline{\sigma}_n}{\partial n} &= -\frac{(2b-d)(a-c+\gamma)}{(n-1)^2\gamma d}+\frac{2(2b-d)b}{(n-1)^2 d\gamma}\sqrt{\left(\frac{a-c}{2b-d+dn}\right)^2+\frac{K}{b}}\\ &\quad +d\frac{(2b-d)(2b+d(n-1))}{(n-1)\gamma d}\left(\left(\frac{a-c}{2b-d+dn}\right)^2+\frac{K}{b}\right)^{-\frac{1}{2}}\left(\frac{a-c}{2b-d+dn}\right)^2(2b-d+dn)^{-1}\\ &< 0\end{aligned} \tag{71}$$

iff

$$-(a-c+\gamma)+2b\sqrt{\left(\frac{a-c}{2b-d+dn}\right)^2+\frac{K}{b}}+(n-1)d\left(\left(\frac{a-c}{2b-d+dn}\right)^2+\frac{K}{b}\right)^{-\frac{1}{2}}\left(\frac{a-c}{2b-d+dn}\right)^2<0 \tag{72}$$

which is an increasing function in K. Therefore, a sufficient condition is that this holds for $\overline{K}$:

$$\overline{K}=b\left(\frac{a-c+\gamma}{2b-d+dn}\right)^2-b\left(\frac{(2b-d)(a-c)-d\gamma}{(2b-d)(2b+d(n-1))}\right)^2 \tag{73}$$

defined by $\Pi_j(1,1,...,1)=\Pi_j(1,0,...,0,\sigma=0)$, $j\neq 1$. This yields:

$$\begin{aligned}&-(a-c+\gamma)+2b\sqrt{\left(\frac{a-c}{2b-d+dn}\right)^2+\left(\frac{a-c+\gamma}{2b-d+dn}\right)^2-\left(\frac{(2b-d)(a-c)-d\gamma}{(2b-d)(2b+d(n-1))}\right)^2}\\ &+(n-1)d\left(\left(\frac{a-c}{2b-d+dn}\right)^2+\left(\frac{a-c+\gamma}{2b-d+dn}\right)^2-\left(\frac{(2b-d)(a-c)-d\gamma}{(2b-d)(2b+d(n-1))}\right)^2\right)^{-\frac{1}{2}}\left(\frac{a-c}{2b-d+dn}\right)^2\\ &< -\frac{(2(a-c)+\gamma)(n-1)d\gamma}{(a-c+\gamma)(2b-d+dn)}<0\end{aligned} \tag{74}$$

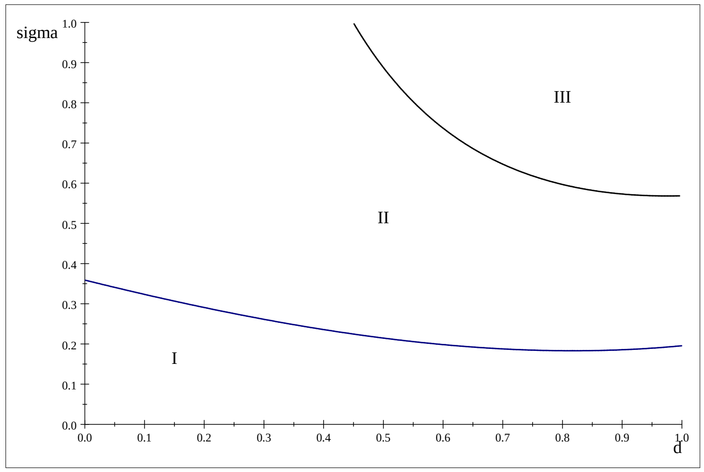

Figure 1: The three regions of model equilibria for $b = 1$, $\gamma = 1$, $a - c = 4$ and $K = 1,5$.

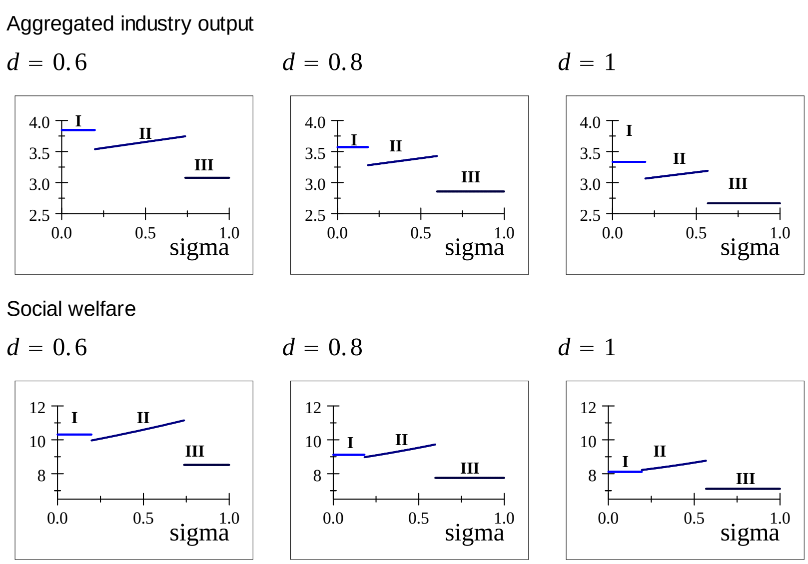

Figure 2: Aggregated industry output and social welfare as functions of σ for $b = 1$, $a - c = 4$, $\gamma = 1$, and $K = 1.5$.

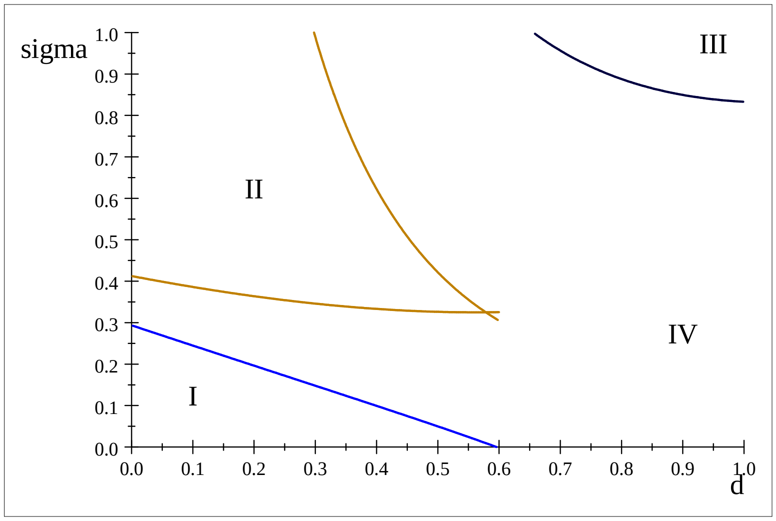

Figure 3: The four regions of model equilibria for $b = 1$, $\gamma = 1$, $M = 8$, $\epsilon = \frac{11}{20}$ and $K = 1.5$.

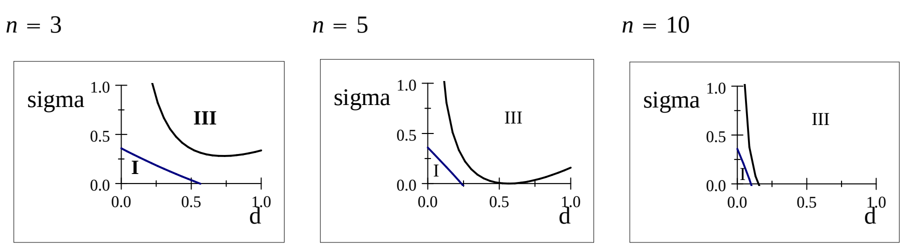

Figure 4: The regions of model equilibria for $b = 1$, $\gamma = 1$, $a - c = 4$ and $K = 1.5$.

CHAPTER III

DIRECT AND INDIRECT SUBSIDIES IN MARKETS WITH SYSTEM GOODS IN THE PRESENCE OF EXTERNALITIES

3.1 Introduction

The adoption of disruptive technologies[1] has recently gained much attention among policy makers. Large funds are destined in order to enhance firms' incentives for adoption of costly emerging technologies. The principal concern of policy makers are markets with externalities, such as environmental impact or national security. In many cases, products in such markets are system goods. This means that consumers derive value from the entire system of components (as for example, mutually compatible charging systems and vehicles, or hardware and software). The set of components that are compatible with one another is determined by firms' choices of technological standards. However, once there is an established technological standard, the transition to superior technologies is often impeded for several reasons. First, there might be a production cost difference between an established and a superior technological standard. For instance, firms can have previous commitments that raise production cost in case of switching to a different standard, which makes the adoption of a superior technological standard unprofitable. Second, once there is an established technological standard, firms might insufficiently engage into the development of other potentially superior technologies. Therefore, the adoption and development of new technologies and products in markets for system goods often depends on public intervention.

The US, the EU, Japan and BRIC countries are especially active in setting policies towards faster technology adoption. For instance, regarding environmental performance, the US provide subsidies to clean technology adopters, car manufacturers and consumers. EU countries introduce high fuel taxes, emission standards for different types of vehicles and the cap-and-trade system, which sets a pollution limit (or cap) allocated to firms in the form of emission permits. Brazil's policy is focused on providing

[1] A disruptive technology is an innovation that disrupts an existing market and replaces an earlier technology creating a new market.

tax reductions and subsidies to the producers of alternative fuels. Similarly to Europe, China applies emission standards and incentive programs, based on funding to support R&D and public procurement of vehicles with low fuel consumption. Japan provides subsidies to consumers of eco-friendly vehicles. Because public funds are scarce, most governments destinate subsidies to particular groups of market players in order to induce the adoption of superior technologies.

As an example for existing policy interventions in these countries consider the market for motor vehicles. The transition to a superior technology (biofuel and electric vehicles) in this market eliminates a negative environmental externality related to the use of an established technology (internal combustion engine vehicles). However, the superior technology implies higher unit production costs. For instance, due to the cost of an electric battery the total cost of an electric vehicle is raised by $12,000 compared to internal combustion engine vehicles.[2] Therefore, once there is an established combustion technology, car manufacturers have few incentives to switch to a superior technology. In addition, because of complementarity between vehicles and charging systems, consumers value a vehicle that is compatible with a larger charging infrastructure. Accordingly, a larger charging infrastructure is deployed for a specific technology if demand for this technology is expected to be higher. As a result, the producers of complementary components have few incentives to adapt their components to the superior technology. Finally, the level of private R&D associated to a superior technology is considered to be suboptimal as car motor producers find it more profitable to improve the performance of an already established technology. Together, all these factors impede the diffusion of electric or biofuel vehicles in the absence of public intervention.

In order to address this problem, high subsidies are provided directly to vehicle manufacturers or indirectly to providers of complementary components (such as energy and fuels) and charging infrastructure deployment. For instance, in 2009 the US-based car manufacturers, namely, Ford Motor, Nissan Motor and Tesla Motors, were awarded $8.5bln. (2.2% of the total US R&D budget) in direct loans as assistance in transition from internal combustion engines to electrified vehicles under the Advanced Technology Vehicles Manufacturing (ATVM) Loan Program. In Brazil, since 1975 the use and production of biofuels (especially, ethanol) were subsidized. Lately, European countries

[2] Federation of American Scientists, Cannis B. (March 2011): "Battery Manufacturing for Hybrid and Electric Vehicles: Policy Issues".

(Germany, France, Denmark, etc.) announced plans of investments into the deployment of charging infrastructure and R&D activities aimed at cost-reduction of electric vehicles. However, in the context of the stimulation of disruptive technology adoption it is still an open issue whether indirect or direct subsidies perform better. For example, Brazil indirectly stimulates the transition to biofuel vehicles. Historically, Brazil depended exclusively on imported fuel, therefore the promotion of in-house ethanol production was launched as a security policy, which later was transformed into an environmental policy. On the contrary, direct subsidies to car manufacturers were chosen in the US. Although, the project of the American Clean Energy and Security Act (ACES 2009) proposed indirect subsidies ($90bln. by 2025) to producers of clean energy technologies (biofuels, electricity generation). This project has not been approved by now, although in 2011 the vast majority of energy subsidies ($24 billion) was spent on renewable energy ($16 billion) according to a government report.[3]

This paper considers the case when both technological standards, the established and the superior, are potentially available and explores firms' incentives for transition from an established technological standard to a superior technological standard. The product is a system good. The components of this good are produced in two markets. The market, in which technological standards are chosen, is imperfectly competitive. Firms act strategically choosing the technological standard for production of their component and the price. The superior technological standard involves a higher unit production cost though a lower negative externality (or a higher positive externality). The market, in which the complementary component is produced, is perfectly competitive. Firms produce their product using an established or a superior technological standard at the same unit production cost. Consumers' purchasing decisions depend on both components' prices and firms' choices of technological standards. It is shown that without policy intervention firms have no incentives to adopt the superior standard. Consequently, we address the design of optimal policies for transition to a superior standard. In particular, we focus on cost-reducing subsidies that can be given to the components' producers that choose a standard or to the producers of a complementary component. The first subsidy directly affects the production cost of firms that adopt a superior technological standard (*direct subsidy*). The second subsidy indirectly affects the firms' incentives for adoption of a superior technological standard by reducing the production cost of an associated component (*indirect subsidy*). The model analyzes

[3]CNN Money, the Congressional Budget Office USA.

welfare implications of direct and indirect cost-reducing subsidies in markets for system goods in the presence of externalities associated to technological standards.[4]

The results in this paper provide a rationale for the implementation of direct or indirect subsidies that enhance firms' incentives for transition to a superior technology. The conditions for optimal subsidies are indicated depending on the cost difference between standards, the externality cost and the presence of consumers' "commitment" to a determined technology. If consumers' purchasing decision is made before the prices of one of the components of the system good are known, policy intervention is desirable only when the externality cost is not lower than the cost difference between standards. Then, if the externality cost is relatively similar to the cost difference between standards, it is optimal to give a direct subsidy to provide incentives for the transition to the superior standard only to the first technology adopter. As the externality cost raises, more technology adopters must be provided with subsidies. This means that in case of direct subsidies, both technology adopters should be given a direct cost-reducing subsidy per unit of production if using the superior standard. In case of indirect subsidies, the necessary amount of cost-reducing subsidies should be given to the producers of the complementary component per volume of production using the superior standard. The comparison between direct and indirect subsidies suggests that if the cost difference between technological standards is high and the externality is low or intermediate, direct subsidies are socially preferable. If the externality cost is high and the technology cost difference is low, direct and indirect subsidies perform equally. However, because the optimal indirect subsidy is higher than the direct subsidy, the direct subsidy leads to higher social welfare. If consumers' purchasing decision is made after the prices of all components of the system good are known, the effects of indirect and direct subsidies' are equal. In this case, if the production cost difference is low, the first adopter might have natural incentives to adopt the superior technology. This means that the adoption of the superior technology implies a lower cost for society. If the production cost difference is high, the adoption requires direct or indirect subsidies. Moreover, the subsidy to the second adopter is higher than the subsidy to the first adopter. Finally, compatibility between components based on different technological standards enhances an advantage of indirect subsidies when both the externality cost and the cost difference

[4] See also Green and Sheshinki (1976), who point out that the presence of substitutes and complements for an externality-causing commodity allows to treat the externality indirectly through the market for related goods.

between an established and a superior technological standard are high.

These results add to the discussion on the choice between direct and indirect subsidies in the markets for system goods. To illustrate this, recall the cases of Brazil and of the US described above. In Brazil, the in-house ethanol production was launched in 1975 due to the highly important environmental and national security concerns. As a result of this policy, by the year 1990, 90% of vehicle manufactures in Brazil used technology allowing to power vehicles by alcohol. According to the results in the present paper, this technology adoption policy is more costly for society in the presence of consumers' "stickiness" to technology, i.e. if consumers are a priori restricted to using the superior or the established technology. In this case indirect subsidies are efficient because at the beginning of new automobile technology adoption consumers by choosing a car are conditioned by the availability of all related infrastructure in their urban area (charging and service stations, parking area). On the contrary, when the infrastructure for both technologies is installed and consumers can make their purchasing decision after the prices for all components are known, both subsidies perform equally. In the US, direct subsidies to car manufacturers were chosen. According to our results, this is the optimal solution at the beginning of superior technology adoption. However, once the infrastructure for both technologies is installed (in other words, in the absence of consumers' "stickiness" to technology), indirect subsidies to producers of clean energy technologies (biofuels, electricity generation) should also be implemented. Similarly, the importance of indirect subsidies is expected to grow in the EU. For example, recently, the deployment of a charging infrastructure all over Europe has been debated. The results of the paper are discussed in the context of optimal subsidy choice to enhance environmental performance in the markets for system goods. However, the results also provide a rationale for optimal subsidy choice in other markets with technology-related externalities, such as national security, for example.

This paper is tightly related to two strands in the literature analyzing technology adoption under different market structures and externalities. The first strand analyzes technology adoption in markets when different technological standards are available. Standards arise in two ways. First, different technologies can be incompatible with each other. Second, producers of the standards can intentionally design technologies to be incompatible. Therefore, the main driving force of technology adoption in such models is compatibility between products chosen by firms. Katz and Shapiro (1992), Regibeau and Rocket (1996), Kristiansen (1998) analyze the timing of product introduction and compatibility between products. Higher compatibility strengthens firms' R&D incentives, which leads to a welfare improving timing of new product introduction. Matutes and Regibeau (1988) show that in a duopoly firms choose full compatibility as an optimal strategy. Moreover, although full compatibility leads to higher prices than incompatibility, it also increases the variety of systems available so that some consumers are better off with compatibility, while others are hurt. The occurrence of standards is tightly related to the presence of network effects, direct or indirect.[5] When a direct network effect is present the size of the installed base positively affects the new standard adoption (Farrel and Saloner, 1986). When an indirect network effect is present, an increase in variety of used technological standards is socially desirable (Church et al, 2008). However, this literature does not provide an insight to the problem of superior technology adoption that arises when the network effect is absent or weak, and the technology adoption is impeded due to the complementarity between components of the system.

The second strand of the literature concerns the choice of optimal policy instruments to address negative externalities, especially, an environmental externality. That regulation affects firms' R&D activities aimed at pollution abatement and development of superior technologies is supported by numerous empirical studies.[6] The theoretical literature discusses the advantages and failures of common policies (subsidies and taxes) and environmental policies (emission and performance standards, tradeable and auctioned permits). The effect of these policies depends on market structure and consumers' preferences for goods. Sartzetakis and Tsigaris (2005) find that in the presence of a direct network effect the tax necessary to induce adoption of a cleaner technology is very high. If tax revenues are earmarked towards subsidizing a cleaner technology, the tax is lower than in the previous case and can be set equal to the marginal external damage. Bansal and Gangopadhyay (2003) compare uniform policies (applied similarly to all firms) and policies that discriminate between firms based on their environmental quality. According to their findings, in the presence of consumers awareness of the externality, uniform as well as discriminatory subsidies reduce total pollution and enhance social welfare. Petrakis and Poyago-Theotoky (1997) argue that technological policies such as R&D subsidies and

[5] The direct network effect means that an increase in the number of consumers directly increases the value for all consumers of the good. The indirect network effect means that an increase in the number of consumers leads to an increase in the value of a complementary good that in turn can increase the value of the original good. For details see Economides and Salop (1992), Economides (1996) and Clements (2004).

[6] See Rennings and Rammer (2009), and Rennings and Rexhauser (2010) for details.

R&D cooperation would generally lead to increased pollution and thus have a negative environmental impact. However, most of the papers mentioned above analyze firms' abatement costs rather than a technological standard choice. An exception is Conrad (2006) who focuses on the problem of the adoption of a cleaner technology in the car market when a direct network effect impedes the technology adoption. He suggests a cost subsidy for the cleaner technology adopters, or, alternatively, the promotion of clean technologies among consumers through advertisement campaigns.

Despite the extensive literature on technology adoption the present paper offers new insights. It differs from the existing literature in two respects. First, it explores the firms' technological standard choice when the network effect is weak or absent. Instead, technology adoption is prevented by the high cost of the superior technology. This provides a benchmark for the firms' strategic choices in markets for system goods when the direct and indirect network effects do not play a crucial role, as for instance, in the vehicle market. Second, it introduces an externality associated to one of the standards. This allows to derive some relevant policy implications.

The reminder of the paper is organized as follows. Section 2 presents the basic framework. Section 3 derives equilibrium outcomes. Section 4 analyzes the effect of direct and indirect subsidies on the firms' technological standard choice. Section 5 presents the results of the model with an alternative timing of consumer choice. Section 6 introduces compatibility between technological standards. Finally, Section 6 discusses policy implications and concludes. Proofs are in the Appendix.

3.2 The model

Consider a product that consists of two complementary components, namely, A and B. Both components are produced in different markets, also denoted as A and B, respectively. Consumer preferences for the composite good are uniformly distributed on the lateral surface of a cylinder. Consumer preferences for component A are given by their location a on the height of the cylinder, while their preferences for component B are given by their location b on the cylinder circle. The height and the circle of the cylinder and the mass of consumers are normalized to 1.

Firms in market A produce component A using one of two technological standards, S ("superior") and E ("established"). The firms that produce components A using technological standard S (the *S-based firms*) are located on the circle at height 0, while firms that produce components A using technological standard E (the *E-based firms*) are located on the circle at height 1. Accordingly, we can interpret consumer location with respect to cylinder height as their preference for change. More "conservative" consumers are located in the upper part of the cylinder in the neighbourhood of 1, while consumers that are eager to change are located in the neighbourhood of 0. Both, S-based and E-based firms produce component A with constant marginal cost c^A. There are no barriers to entry in market A such that perfectly competitive prices equal marginal cost.[7]

Market B is assumed to be imperfectly competitive. Concretely, we assume a duopoly structure. As in Salop (1979), the two firms are located equidistantly on the cylinder unit circle. If a firm in market B uses technological standard S it locates on the bottom circle of the cylinder while if it uses technological standard E it locates on the top circle of the cylinder. Thus, we can have three different scenarios of firm locations, which are represented in Figure 5. Both firms can either produce with the same standard S or E, or use different standards. The unit production cost of firms in market B is c^{BS} if they use technological standard S and c^{BE} if they use technological standard E. The cost difference of using a superior technological standard is given by $\delta = c^{BS} - c^{BE} > 0$. Furthermore, firms in market B incur a fixed cost F.

The consumers' choice of a specific composite good depends on its distance to their preferred option, its price and the distance and price of alternative composite goods. Denote the unit travel cost associated to the components A and B as t^A and t^B. t^A reflects the disutility of using a non-ideal component A with respect to the taste for change, while t^B is the disutility of being located at a distance from the nearest variety of component B. For simplicity, we assume that $t^A = t^B = t > 0$. Prices of components A and B based on standard $k = S, E$ are denoted p^{Ak} and p^{Bk}, respectively. Firm i's demand on component B based on standard k is D_i^k. The total value a consumer derives from using a composite good is U_0. Consumers' reservation utility is 0. This Section assumes that components A and B based on different technological standards are incompatible.[8] Consequently, a consumer located at (a, b) that buys S-based components A and B has utility $U^{SS} = U_0 - p^{AS} - a^2 t^A - p^{BS} - b^2 t^B$.

[7] The structure of the market for the complementary component reflects the absence of strategical interactions between firms. Examples of complementary component producers for the car market can be petrol stations and electricity producers. The market for petrol is close to perfectly competitive, and the electricity market is regulated. Therefore, the producers do not directly compete with each other. The assumption of perfectly competitive pricing simplifies calculations. However, if there were one provider of each technology, the qualitative results would be the same, but with higher prices for component A.

[8] Perfect compatibility between technological standards is introduced in Section 6.

Analogically, the expression for U^{EE} is derived. The transportation costs are quadratic. This implies that the demand and profit functions are continuous and concave and firms in market B have incentives to locate equidistantly in equilibrium.[9] We assume that $U_0 > p^{Ak} + t^A + p^{Bk} + t^B$, which guarantees that consumers always buy a composite good.

The established standard has a negative externality. The cost of the externality is quadratic in total quantity of E-based system goods. The damage function is $\varepsilon \left(\sum_{i=1,2} D_i^E\right)^2 /2$, where $\varepsilon > 0$ indicates the severity of damage. Define social welfare W as the sum of consumers' surplus, firms' profits and externality costs. For the different scenarios we obtain:

$$W(S,S) = 4\int_0^{\frac{1}{4}}\int_0^{1}\left(U_0 - p^{AS} - p^{BS} - x^2t^A - y^2t^B\right)dxdy + 2\Pi_i^B(S;S), \tag{75}$$

$$W(E,E) = 4\int_0^{\frac{1}{4}}\int_0^{1}\left(U_0 - p^{AE} - p^{BE} - (1-x)^2t^A - y^2t^B\right)dxdy + 2\Pi_i^B(E;E) - \frac{\varepsilon}{2}, \tag{76}$$

$$\begin{aligned} W(S,E) = {} & 2\int_0^{\frac{1}{2}}\int_0^{a(b)}\left(U_0 - p^{AS} - p^{BS} - x^2t^A - y^2t^B\right)dxdy \\ & +2\int_0^{\frac{1}{2}}\int_{a(b)}^{1}\left(U_0 - p^{AE} - p^{BE} - (1-x)^2t^A - \left(\frac{1}{2}-y\right)^2t^B\right)dxdy \\ & +\Pi_1^B(S;E) + \Pi_2^B(E;S) - \frac{\varepsilon}{2}\left(D_2^E\right)^2, \end{aligned} \tag{77}$$

where $\Pi_i^B(k;l) = \left(p_i^{Bk} - c_i^{Bk}\right)D_i^k$, $k,l = S,E$, is firm i's profit in market B when it uses standard k and its rival uses standard l.

The timing of the interaction between the policy maker and firms in markets A and B is the following. In stage 0, policy makers choose between no intervention or a cost-reducing subsidy s^A or s^B to be given to firms in markets A or B, respectively. In stage 1, the price of component A is determined. In stage 2, the two firms in market B choose a technological standard, S or E, for production. In stage 3, consumers decide on the system good they buy. In stage 4, the prices of components B are determined and consumers buy the system good. The solution concept is Subgame Perfect Nash Equilibrium (SPNE) and the game is solved by backward induction.

This model describes a market structure that can be relevant for the analysis of a number of

[9] For further details see Economides (1989).

markets for system goods. Market A is represented by a unit line. Consumers location on this line reflects their preferences with respect to the two opposed standards. Such preferences can be caused by environmental awareness or the taste for change. If a consumer is located in the neighbourhood of S-based producers, she would choose the S-based component unless its price is very high relative to transportation cost or the market for S-based component A disappears because both firms in market B chose standard E. At the same time, in market B consumers are distributed along the unit circle. Such preferences mean that consumers consider both existing products, and their product choices are more sensitive to changes in product prices.

An example for markets of a system good with such a structure are markets for vehicles and energy sources. When a vehicle is purchased, consumers might have preferences regarding the fuel and charging system, while vehicles are considered as similar products. The value derived from a specific vehicle increases when its fuel becomes more available and at a cheaper price. Therefore, due to complementarity between markets, vehicle producers are "locked-in" with an established technology, even if it causes a negative environmental externality. As another example, consider the market for global navigation systems (GNS) and services for civilian use (in all modes of transport, precision agriculture and personal mobility) or signal adopters. The GNS hardware is usually elaborated by the public sector, while services are provided by private firms. In Europe, private firms design their services choosing the signal source between an established foreign technology (for instance, GPS, which belongs to the US) and a national technology (Galileo). The use of the latter generates a positive externality for national security reasons because with Galileo the ESA (European Space Agency) has control over the signal availability. Therefore, national governments aiming to promote national GNS must provide incentives to producers of services to switch to national technological standards.

An important assumption of the model in this paper is that consumers decide on the system good they prefer to buy before the prices for the component in market B are derived. An example, for such a decision structure is the choice between a car with an electric or an internal combustion engine. Once consumers committed to the technology by their choice of component A (i.e. a parking place and all related infrastructure for an electric or a gasoline car in their living area) they are conditioned in their choice of component B (i.e. cars) even when cars based on both technologies are available. In the case of GNS signal receivers that are built into cell phones or vehicles, consumers, firstly, buy a signal receiver (i.e. hardware) disposing information about the availability of services based on the established (for instance, GPS) and the new technology (Galileo). Once the hardware is bought, consumers are conditioned to use the services based on the same standard as their receivers and are less sensible to the price of the service. Alternatively, in the case of public procurement, once the municipal authority has information regarding the availability of vehicles based on a foreign and national technology, the decision of public procurement is made taking into consideration political issues. This assumption is reasonable in the context of the problem of technology adoption since the components B (cars, GNS services) are introduced more frequently than the components A (energy sources, GNS hardware). Nevertheless, components A determine the technological standard and involve permanent future cost for consumers. Therefore, their price plays a more important role in the decision to buy an S- or E-based system good. Section 5 analyzes optimal policy design under the alternative assumption that consumers make the choice of the system good before the prices on component B are derived and compares the results to the basic framework.

3.3 Equilibrium 'laissez faire' outcomes

In stage 4, firms in market B compete as in the Salop model. In equilibrium, firms locate at maximum distance on the circle.[10] For convenience, denote the location of firm 1 by $b = 0$ and that of firm 2 by $b = 1/2$. If both firms commit to the same technological standard k, the consumer indifferent between the components produced by the two firms are situated at $b^k = \left(p_2^{Bk} - p_1^{Bk}\right)/t + 1/4$. So, the equilibrium demand of firm 1 is $D_1^k = 2b^k$ and that of firm 2 is $D_2^k = 1 - 2b^k$. Prices are determined by profit maximization as $p^{Bk} = c^{Bk} + t/4$. Thus, stage 3 equilibrium profits are:

$$\Pi_i^B\left(S;S\right) = \Pi_i^B\left(E;E\right) = \frac{t}{8} - F,\ i = 1,2. \tag{78}$$

If the two firms in market B commit to different technologies the consumer indifferent between the S-based and E-based component is located at $b = \left(p_2^{BE} - p_1^{BS}\right)/t + 1/4$.[11] Consequently, equilibrium prices are:

$$p^{BS} = \frac{8c^{BS} + 4c^{BE} + 3t}{12} \quad \text{and} \quad p^{BE} = \frac{8c^{BE} + 4c^{BS} + 3t}{12}. \tag{79}$$

[10] See Salop (1979) and Economides (1989) for details.

[11] Without loss of generality assume that a firm 1 chooses a technological standard S and a firm 2 chooses a technological standard E.

Consumer product choice in stage 3 depends on the technological standards chosen by the firms in market B. Three scenarios can be distinguished. If both firms in market B choose standard S, i.e. locate at $a = 0$, the market share of the S-based standard is 1. If both firms in market B choose standard E, i.e. locate at $a = 1$, the market share of the E-based standard is 1. Finally, if one firm in market B chooses an S-based technological standard and the other firm chooses an E-based technological standard, the demand of each firm is determined by the location of the consumer indifferent between the S- and E-based system good. From $U^{SS} = U^{EE}$ we obtain her location:

$$a \equiv a(b) = \frac{1}{2t}\left(p^{AE} - p^{AS} + p^{BE} - p^{BS} + \frac{5}{4}t - bt\right). \tag{80}$$

Regarding the location of indifferent consumers we make the following assumption:

Assumption 1. Let $0 < a(b) < 1$, $\forall b \in (0, 1/2)$.

This assumption guarantees that both firms in market B always have positive demand independently of the standard they adopt. This allows to eliminate trivial cases.

The market share in market B for an S-based and an E-based technology can be calculated as the area of a trapezoid with an upper bound determined by (80) which indicates the location of indifferent consumers between the S- and the E-based system. As market A is perfectly competitive, all players anticipate that stage 1 equilibrium prices are $p^{Ak} = c^A$. Thus, after substituting (79) into (80) we obtain

$$a \equiv \frac{5}{8} - \frac{b}{2} - \frac{\delta}{6t}. \tag{81}$$

Consequently, equilibrium demand is given by

$$D_1^S = \frac{a(0) + a(1/2)}{2} = \frac{1}{2} - \frac{\delta}{6t} \tag{82}$$

and stage 4 equilibrium profits are:

$$\Pi_1^B(S;E) = \frac{(3t - 4\delta)(3t - \delta)}{72t} - F \quad \text{and} \tag{83}$$

$$\Pi_2^B(E;S) = \frac{(3t + 4\delta)(3t + \delta)}{72t} - F. \tag{84}$$

In stage 2, firms in market B choose technological standards. By definition, E is the established standard in the market. This standard has lower unit production costs but generates a negative externality. Comparing the payoffs in equation (78) with those in equations (83) and (84) we obtain the following result.

Lemma 1 *Neither the first firm, nor the second firm have incentives to switch to a superior standard in the absence of policy interventions.*

Proof:

Firm 1 will switch to a superior standard iff $\Pi_1^B(S;E) > \Pi_1^B(E;E)$. From equations (78) and (83) we find that this is equivalent to $15t - 4\delta < 0$. Substituting into (81), this yields $a < -b/2$ which contradicts assumption 1. On the other hand, if one firm has adopted standard S, say firm 1, the second firm changes from E to S iff $\Pi_2^B(S;S) > \Pi_2^B(E;S)$. This is equivalent to $9t + 2\delta < 0$, which contradicts $t > 0$ and $\delta > 0$. Therefore, for any rival's strategy neither firm has incentives to switch to the superior technological standard S. **q.e.d.**

Finally, in perfectly competitive market A the prices for an S- and an E-based component A are determined in stage 1. In order to choose the optimal policy intervention, in the following section the equilibrium outcomes are derived for different types of technological policies, concretely, indirect and direct subsidies.

3.4 Subsidies

3.4.1 The indirect subsidy

As a policy intervention consider a subsidy to S-based firms in market A. The objective of this subsidy is to reduce production costs (and prices) of the S-based component A and thereby of the S-based composite good. This increases demand and profits of firms in market B that adopt standard S. So, the subsidy indirectly increases firms' incentives in market B to adopt the superior standard. We call this kind of subsidy an *indirect subsidy* and denote it by s^A.

Because market A is perfectly competitive, the indirect subsidy decreases equilibrium prices $p^{AS} = c^A - s^A$ while the price of E-based producers remains $p^{AE} = c^A$. Equilibrium prices in market B are not affected by this subsidy and are given by (79). Substituting these prices into equation (80) we obtain for the location of indifferent consumers between S- and E-based composite goods:

$$a^A \equiv a^A(b) = \frac{5}{8} - \frac{b}{2} - \frac{\delta}{6t} + \frac{s^A}{2t}. \tag{85}$$

This expression corresponds to (81) with a subsidy in market A. Notice, that Assumption 1 requires that $0 < s^A < \frac{9t+4\delta}{12}$.

Stage 3 equilibrium demand is:

$$D_1^S = \frac{3t-\delta+3s^A}{6t} \quad \text{and} \quad D_2^E = \frac{3t+\delta-3s^A}{6t} \tag{86}$$

If firms in market B choose the same standard their profits are the same as in the basic framework without subsidies and given by (78). If firms choose different standards, their profits are:

$$\Pi_1^B(S;E) = \frac{(3t-4\delta)\left(3t-\delta+3s^A\right)}{72t} - F \tag{87}$$

$$\Pi_2^B(E;S) = \frac{(3t+4\delta)\left(3t+\delta-3s^A\right)}{72t} - F. \tag{88}$$

The cost of the subsidy is $s^A \sum_{i=1,2} D_i^S$, where $\sum_i D_i^S$ is the total quantity of the S-based systems sold. With the indirect subsidy, social welfare is given by:

$$W^A(S,S) = 4\int_0^{\frac{1}{4}}\int_0^1 \left(U_0 - p^{AS} - p^{BS} - x^2t - y^2t\right)dxdy + 2\Pi_i^B(S;S) - s^A, \tag{89}$$

$$W^A(E,E) = 4\int_0^{\frac{1}{4}}\int_0^1 \left(U_0 - p^{AE} - p^{BE} - (1-x)^2t - y^2t\right)dxdy + 2\Pi_i^B(E;E) - \frac{\varepsilon}{2}, \tag{90}$$

$$\begin{aligned} W^A(S,E) = {} & 2\int_0^{\frac{1}{2}}\int_0^{a^A(b)} \left(U_0 - p^{AS} - p^{BS} - x^2t - y^2t\right)dxdy \\ & +2\int_0^{\frac{1}{2}}\int_{a^A(b)}^1 \left(U_0 - p^{AE} - p^{BE} - (1-x)^2t - \left(\frac{1}{2}-y\right)^2 t\right)dxdy \\ & +\Pi_1^B(S;E) + \Pi_2^B(E;S) - \frac{\varepsilon}{2}\left(D_2^E\right)^2 - s^A D_1^S. \end{aligned} \tag{91}$$

From Lemma 1 we know that policy makers must pay a positive subsidy to incite firms in market B to switch from standard E to standard S. Consider the minimum subsidy to firms in market A necessary to incite the first and the second firm in market B to adopt standard S. Comparing the payoffs in equation (78) with those in equations (87) and (88) we obtain the following result.

Lemma 2. *Given an E-based or an S-based firm in market B, its rival adopts a superior standard S, if S-based firms in market A get a subsidy* $s \geq \underline{s}_1^A \equiv \delta\frac{15t-4\delta}{9t-12\delta}$. *Given an S-based firm in market B, its* *rival adopts a superior standard S if it gets a subsidy* $s \geq \underline{s}_2^A = \delta\frac{15t+4\delta}{9t+12\delta}$*. The subsidy* $\underline{s}_1^A$ *is sufficient to make both firms in market B to adopt a superior standard S, i.e.* $\underline{s}_1^A > \underline{s}_2^A$*.*

Proof:

Firm 1 will change to a superior standard iff $\Pi_1^B(S;E) > \Pi_1^B(E;E)$. From equations (87) and (78) we find that this is true for $s \geq \underline{s}_1^A \equiv \delta\frac{15t-4\delta}{9t-12\delta}$. On the other hand, if one firm has adopted standard S, say firm 1, the second firm changes from E to S iff $\Pi_2^B(S;S) > \Pi_2^B(E;S)$. From equations (88) and (78) we find that this is true if $s \geq \underline{s}_2^A \equiv \delta\frac{15t+4\delta}{9t+12\delta}$. Because $\underline{s}_1^A > \underline{s}_2^A$, $\underline{s}_1^A$ is a sufficient subsidy for S-based producers in market A to induce both firms in market B to adopt standard S [12]. **q.e.d.**

To find the welfare maximizing indirect subsidies to a first and a second adopter of standard S, the policy maker must solve the following problem:

$$s^A = \arg\max\left\{W^A(E,E),\ \max_{s^A \geq \underline{s}_1^A} W^A(S,S)\right\} \tag{92}$$

We get the following result:

Proposition 1. The welfare maximizing indirect subsidies to firms in market A are:

$$s^A = \begin{cases} 0 & \text{for} \quad 0 \leq \varepsilon/t \leq \epsilon_1 \quad \text{(Region I)} \\ \underline{s}_1^A & \text{for} \quad \epsilon_1 < \varepsilon/t \quad \text{(Region III)} \end{cases}$$

where $\epsilon_1 = 2(\delta/t)$ and $\delta/t < \frac{9}{28}$.

Proof. In the Appendix.

The two regions are displayed in Figure 6. Intuitively, policy intervention is desirable only when the impact of the externality is high in comparison to the cost difference between the two standards. However, the more important the externality becomes, the more technology adopters must be targeted with subsidies. Therefore, if δ/t is low and the negative externality is high, the optimal subsidy to the firms in market A is $\underline{s}_1^A$. With this subsidy, both firms in market B adopt standard S.

[12] The existence of a sufficient minimum subsidy that affects firms' technology choice is supported by empirical evidence. For instance, the analysis of Aschhoff (2009) for Germany suggests that public R&D grants should have a minimum size to cause an impact on a firm's privately financed R&D.

3.4.2 The direct subsidy

The second policy intervention considered in this paper is a subsidy to S-based firms in market B. This subsidy reduces the production cost and the price of the S-based component B. This increases the demand on the S-based system good and, consequently, the profits of superior technology adopters in market B. Therefore, this subsidy directly increases firms' incentives in market B to adopt the superior standard. We call this kind of subsidy a *direct subsidy* and denote it by s^B.

The direct subsidy doesn't affect equilibrium prices in market A, so they remain $p^{AS} = p^{AE} = c^A$. However, it affects equilibrium prices of S-based firms in market B. If both firms adopt S, the prices are $p_i^{BS} = c_1^{BS} - s^B + t/4$. If both firms choose the same technological standard, the resulting profits of firms in market B are equal to (78). If firms B choose different standards, the equilibrium prices are:

$$p_1^{BS} = \frac{2\left(c^{BS} - s^B\right)}{3} + \frac{c^{BE}}{3} + \frac{t}{4} \text{ and } p_2^{BE} = \frac{2c^{BE}}{3} + \frac{\left(c^{BS} - s^B\right)}{3} + \frac{t}{4} \tag{93}$$

Plugging (93) into (80) we obtain for the location of indifferent consumers between S- and E-based composite goods:

$$a^B \equiv a^B(b) = \frac{5}{8} - \frac{b}{2} - \frac{\delta}{6t} + \frac{s^B}{6t}. \tag{94}$$

This is the corresponding expression to (81) with a subsidy in market B. Stage 3 equilibrium demand is:

$$D_1^S = \frac{3t - \delta + s^B}{6t} \quad \text{and} \quad D_2^E = \frac{3t + \delta - s^B}{6t} \tag{95}$$

If firms in market B choose the same standard their profits are the same as in the case without subsidies and given by (78). If firms choose different standards, their profits are:

$$\Pi_1^B(S; E) = \frac{\left(3t - \delta + s^B\right)\left(3t - 4\delta + 4s^B\right)}{72t} - F, \tag{96}$$

$$\Pi_2^B(E; S) = \frac{\left(3t + \delta - s^B\right)\left(3t + 4\delta - 4s^B\right)}{72t} - F. \tag{97}$$

Again, the cost of the subsidy is $s^B \sum_{i=1,2} D_i^S$, where $\sum_i D_i^S$ is the total quantity of the S-based systems sold. Thus, with the direct subsidy, social welfare is given by:

$$W^B(S;S) = 4\int_0^{\frac{1}{4}}\int_0^1 \left(U_0 - p^{AS} - p^{BS} - x^2t - y^2t\right)dxdy + 2\Pi_i^B(S;S) - s^B, \tag{98}$$

$$W^B(E;E) = 4\int_0^{\frac{1}{4}}\int_0^1 \left(U_0 - p^{AE} - p^{BE} - (1-x)^2t - y^2t\right)dxdy + 2\Pi_i^B(E;E) - \frac{\varepsilon}{2}, \tag{99}$$

$$\begin{aligned} W^B(S;E) = {} & 2\int_0^{\frac{1}{2}}\int_0^{a^B(b)} \left(U_0 - p^{AS} - p^{BS} - x^2t - y^2t\right)dxdy \\ & +2\int_0^{\frac{1}{2}}\int_{a^B(b)}^1 \left(U_0 - p^{AE} - p^{BE} - (1-x)^2t - \left(\frac{1}{2} - y\right)^2 t\right)dxdy \\ & +\Pi_1^B(S;E) + \Pi_2^B(E;S) - \frac{\varepsilon}{2}\left(D_2^E\right)^2 - s^B D_1^S. \end{aligned} \tag{100}$$

First, consider the minimum subsidy necessary to incite the first firm to adopt standard S. Second, consider the minimum subsidy necessary to incite the second firm to adopt standard S. Comparing the payoffs in equation (78) with those in equations (96) and (97) we obtain the following result.

Lemma 3. *Given an E-based firm in market B, its rival adopts a superior standard S, if it gets a subsidy* $s \geq \underline{s}_1^B \equiv \delta$*. Similarly, given an S-based firm in market B, its rival adopts a superior standard S if it gets a subsidy* $s \geq \underline{s}_2^B \equiv \delta$*.*

Proof:

Firm 1 will change to a superior standard iff $\Pi_1^B(S;E) > \Pi_1^B(E;E)$. From equations (96) and (78) we find that this is true for $s \geq \underline{s}_1^B \equiv \delta$. On the other hand, if one firm has adopted standard S, say firm 1, the second firm changes from E to S iff $\Pi_2^B(S;S) > \Pi_2^B(E;S)$. From equations (97) and (78) we find that this is true if $s \geq \underline{s}_2^B = \delta$. **q.e.d.**

The results in Lemmas 2 and 3 suggests that the incentives provided by the direct and indirect subsidies to the firms in the market B are distinct. The minimum subsidy to the S-based firms A affects firms B' standard choice depending on the relation between the unit cost difference and the transportation cost, i.e. the disutility of being far from the most preferred variety. The subsidy to the S-based producers in market B provides sufficient incentives only if it is higher than the unit production cost difference between the two technological standards.

To find the welfare maximizing direct subsidies to the first and the second adopter of standard S, the policy maker must solve the problem:

$$\left(s_1^B, s_2^B\right) = \arg\max \left\{ W^B\left(E,E\right), \max_{s_1^B \geq \underline{s}_1^B} W^B\left(S,E\right), \max_{s_1^B \geq \underline{s}_1^B, s_2^B \geq \underline{s}_2^B} W^B\left(S,S\right) \right\}.$$

The following result is obtained:

Proposition 2. For all δ the welfare maximizing direct subsidies to firms in market A are:

$$\left(s_1^B, s_2^B\right) = \begin{cases} (0,0) & \text{for} \quad 0 < \varepsilon/t \leq \epsilon_2 & \text{(Region I)} \\ (\underline{s}_1^B, 0) & \text{for} \quad \epsilon_2 < \varepsilon/t \leq \epsilon_3 & \text{(Region II')} \\ (s_{\max}^B, 0) & \text{for} \quad \epsilon_3 < \varepsilon/t \leq \epsilon_4 \text{ and } \varepsilon/t \leq \epsilon_5 & \text{(Region II")} \\ (\underline{s}_1^B, \underline{s}_2^B) & \text{for} \quad \epsilon_4 < \varepsilon/t & \text{(Region III)} \end{cases}$$

where $s_{\max}^B = \frac{(3t+\delta)\varepsilon - 4t\delta - t^2}{2t+\varepsilon}$, $\epsilon_2 = \frac{4}{3}\left(\delta/t\right) - \frac{49}{72}$, $\epsilon_3 = 2\left(\delta/t\right) + \frac{1}{3}$, $\epsilon_4 = \frac{32}{5}\left(\delta/t\right)^2 + \frac{224}{15}\left(\delta/t\right) + \frac{302}{45}$, $\epsilon_5 = 8\left(\delta/t\right) + \frac{22}{3}$, with $\epsilon_2 < \epsilon_3 < \epsilon_4$ and $\delta/t < \frac{9}{4}$.

Proof. In the Appendix.

The four regions are displayed in Figure 7. When the unit production cost with the superior standard is very high and the negative externality is low, no subsidy is the best policy. Then, for lower delta, $\underline{s}_1^B$ must be given to the first adopter of the superior standard S in market B. When both δ/t and the negative externality are relatively high, $s_{\max}^B$ yields higher social welfare. Similarly, it induces firm 1 in market B to adopt standard S. Finally, when δ/t is very low provided the high level of a negative externality, the optimal policy is to provide $\underline{s}_1^B$ and $\underline{s}_2^B$ to induce both firms in market B to adopt S.

3.4.3 The choice of optimal policy

Comparing social welfare under optimal indirect and direct subsidies, i.e. the results in Propositions 1 and 2, we obtain the following proposition.

Proposition 3. The optimal policy intervention is determined by the following optimal subsidies:

$$(s_1, s_2) = \begin{cases} (\underline{s}_1^B, 0) & \text{for} \quad 0 < \varepsilon/t \leq \epsilon_3 & \text{(Region 2'B)} \\ (s_{\max}^B, 0) & \text{for} \quad \epsilon_3 < \varepsilon/t \leq \epsilon_4 \text{ and } \varepsilon/t \leq \epsilon_5 & \text{(Region 2"B)} \\ \{\underline{s}_1^A, (\underline{s}_1^B, \underline{s}_2^B)\} & \text{for} \quad \epsilon_4 < \varepsilon/t & \text{(Region 3AB)} \end{cases}$$

where $0 \leq \delta/t \leq 9/28$, $\underline{s}_1^A > \underline{s}_1^B$. Social welfare is higher with a direct subsidy in Regions 2 and 3 and is equal with indirect and direct subsidies in Region 4.

Proof. In the Appendix.

The different regions are displayed in Figure 8. Given the range of values for the production cost difference between the standards, providing a direct or an indirect subsidy such that at least to one firm adopts a superior technology is socially preferable to no intervention. Though social welfare is equal with direct and indirect subsidies in Region 3AB, notice that a welfare maximizing direct subsidy in this region is lower than an indirect subsidy. Therefore, a direct subsidy provided to S-based firms in market B is socially preferable in the presence of costly public fund raising (due to administrative costs or corruption). Then, a lower subsidy leads to a lower efficiency loss. Remarkably, this result suggests the implementation of direct subsidies despite the fact that the positive effect of an indirect subsidy on the adoption of a superior technology by consumers is higher than the effect of a direct subsidy in the model[13].

3.5 An alternative timing of consumer choice

This section reexamines the basic model introducing a modification in the timing of the game. Consider that, now, consumers choose the system good when the prices of components A and B are determined. As in Section 2, in stage 0, policy makers choose between a cost-reducing subsidy s^A or s^B to be given to firms in markets A or B, respectively. In stage 1, the price of component A is determined. In stage 2, the two firms in market B choose a technological standard, S or E, for production. In stage 3, the prices of components B are determined and consumers buy the composite good.

In stage 3, consumers choose the system good. If both firms in market B choose the same technological standard, S or E, the resulting outcomes are the same as in Section 2. Similarly, if firms in market B choose different technological standards, S and E, the indifferent consumer is determined by (80). However, the demand functions of firms B are now affected by their own prices and the prices of the complementary good. Calculating demand as in (82) we obtain:

$$D_1^S = \frac{t + p^{AE} - p^{AS} - p^{BS} + p^{BE}}{2t} \quad \text{and} \quad D_2^E = \frac{t + p^{AS} + p^{BS} - p^{AE} - p^{BE}}{2t}.$$

[13] $\frac{\partial a^A}{\partial s^A} > \frac{\partial a^B}{\partial s^B}$

Consequently, stage 3 equilibrium prices are:

$$p_1^{BS} = \frac{3t + 2c_1^{BS} + c_2^{BE} - p^{AS} + p^{AE}}{3} \quad \text{and} \quad p_2^{BE} = \frac{3t + c_1^{BS} + 2c_2^{BE} + p^{AS} - p^{AE}}{3}.$$

Again, in stage 1, $p^{Ak} = c^A$. The resulting payoffs of firms in market B are

$$\Pi_1^S(S, E) = \frac{(3t - \delta)^2}{18t} - F \quad \text{and} \quad \Pi_2^E(S, E) = \frac{(3t + \delta)^2}{18t} - F. \tag{101}$$

Lemma 4 *Neither the first firm, nor the second firm have incentives to switch to a superior standard in the absence of policy interventions for $\frac{3}{2}t < \delta < \frac{9}{4}t$. The first firm chooses a superior standard and the second firm chooses an established standard in the absence of policy interventions for $0 < \delta < \frac{3}{2}t$.*

Proof:

Firm 1 will change to a superior standard iff $\Pi_1^B(S; E) > \Pi_1^B(E; E)$. From equations (101) and (78) we find that this is true for $0 < \delta < \frac{3}{2}t$. On the other hand, for $\frac{3}{2}t < \delta < \frac{9}{4}t$ neither the first nor the second firm will change to a superior standard as $\Pi_1^B(E; E) > \Pi_1^B(S; E)$ and $\Pi_2^B(E; S) > \Pi_2^B(S; S)$.
q.e.d.

If an indirect subsidy is given to S-based firms in market A, this increases the prices of the S-based firm in market B and decreases the prices of the E-based firm in market B. This is because consumers' choice will be shifted towards an S-based system good and firms in market B can anticipate that adjusting their prices:

$$p_1^{BS} = \frac{3t + 2c^{BS} + c^{BE} + s^A}{3} \quad \text{and} \quad p_2^{BE} = \frac{3t + c^{BS} + 2c^{BE} - s^A}{3}. \tag{102}$$

The demands are also affected by change in prices in market A:

$$D_1^S = \frac{3t - \delta + s^A}{6t} \quad \text{and} \quad D_2^E = \frac{3t + \delta - s^A}{6t}. \tag{103}$$

The resulting payoffs are:

$$\Pi_1^S(S, E) = \frac{\left(3t - \delta + s^A\right)^2}{18t} - F \quad \text{and} \quad \Pi_2^E(S, E) = \frac{\left(3t + \delta - s^A\right)^2}{18t} - F. \tag{104}$$

If a direct subsidy is given to firms in market B, this decreases the prices of both firms in market B, although it affects p_1^{BS} more than p_2^{BE}:

$$p_1^{BS} = \frac{3t + 2c^{BS} + c^{BE} - 2s^B}{3} \text{ and } p_2^{BE} = \frac{3t + c^{BS} + 2c^{BE} - s^B}{3}.$$

The resulting demands are equal to 103. Because an S-based firm in market B is given direct subsidies, the resulting payoffs are the same as 104.

Lemma 5. *Given an E-based firm in market B, its rival adopts a superior standard S, if it gets a subsidy* $s \geq \underline{s}_1^A \equiv \underline{s}_1^B \equiv \delta - \frac{3}{2}t$*. Similarly, given an S-based firm in market B, its rival adopts a superior standard S if it gets a subsidy* $s \geq \underline{s}_1^A \equiv \underline{s}_1^B \equiv \delta + \frac{3}{2}t$*. Furthermore, the subsidy to the first adopter is lower than the subsidy to the second adopter, i.e.* $\underline{s}_1^A \equiv \underline{s}_1^B < \underline{s}_2^A \equiv \underline{s}_2^B$.

Proof:

Firm 1 will change to a superior standard iff $\Pi_1^B(S;E) > \Pi_1^B(E;E)$. From equations (104) and (78) we find that this is true for $s \geq \underline{s} \equiv \delta - \frac{3}{2}t$. Similarly, if one firm has adopted standard S, say firm 1, the second firm changes from E to S iff $\Pi_2^B(S;S) > \Pi_2^B(E;S)$. From equations (104) and (78) we find that this is true if $s \geq \underline{s}_2 \equiv \delta + \frac{3}{2}t$.

Comparing the minimum subsidies obtained in Section 4 and Section 5 we obtain the following proposition.

Proposition 4. In the absence of consumers' commitment to the technology the optimal policy intervention is determined by the following optimal subsidies:

$$(s_1, s_2) = \begin{cases} (0,0) & \text{for } 0 < \varepsilon/t \leq \epsilon_7 \text{ and } 0 < \delta/t \leq 3/2 & \text{(Region 1)} \\ \{(\underline{s}_1^A, 0), (\underline{s}_1^B, 0)\} & \text{for } 0 < \varepsilon/t \leq \epsilon_8 \text{ and } 3/2 < \delta/t \leq 9/4 & \text{(Region 2'AB)} \\ \{(s_{\max}^A, 0), (s_{\max}^B, 0)\} & \text{for } \epsilon_8 < \varepsilon/t \leq \epsilon_9 \text{ and } 3/2 < \delta/t \leq 9/4 & \text{(Region 2"AB)} \\ \{(\underline{s}_1^A, \underline{s}_2^A), (\underline{s}_1^B, \underline{s}_2^B)\} & \text{for } \epsilon_7 < \varepsilon/t \text{ and } 0 < \delta/t \leq 3/2 & \text{(Region 3AB)} \\ \{(\underline{s}_1^A, \underline{s}_2^A), (\underline{s}_1^B, \underline{s}_2^B)\} & \text{for } \epsilon_9 < \varepsilon/t \text{ and } 3/2 < \delta/t \leq 9/4 & \text{(Region 3AB)} \end{cases}$$

where $\epsilon_7 = \frac{304(\delta/t)+80(\delta/t)^2+147}{48(\delta/t)+8(\delta/t)^2+72}$, $\epsilon_8 =, \frac{4}{3}(\delta/t) - \frac{4}{9}$, $\epsilon_9 = \frac{32}{5}(\delta/t)^2 + \frac{224}{15}(\delta/t) + \frac{302}{45}$.

Proof. In the Appendix.

The five regions are displayed in Figure 9. Interestingly, given a relatively low cost difference between two standards and a low externality cost, the first firm in market B adopts a superior technological standard even in the absence of policy intervention. The fact that consumers choose the system good after all prices are known, decreases the indirect and direct subsidies that are needed to provide sufficient incentives to the first adopter of technological standard S, but raises the subsidies to the second adopter. This result suggests that consumers' ex ante decision regarding the system good to be purchased (or a "commitment" to a certain technology caused, for instance,by the availability of infrastructure for using a system good based on a determined technology) creates inefficiencies increasing the optimal size of the subsidies in the beginning of adoption. The higher is the degree of consumers' "commitment" the more we move from the situation, in which indirect and direct subsidies perform equally, towards the situation, in which the direct subsidy is preferable.

The comparison of two scenarios, the basic framework and the alternative timing, provides intuition on the choice of the optimal subsidy in a dynamic context of new technology adoption. In an early stage of technology adoption, when the initial cost difference between the established and superior technology is crucial and consumers are "locked-in" with a certain technology, it is better to provide direct subsidies to firms that potentially adopt superior technologies. Further, when the consumers' restriction does not dominate, and their purchasing decisions are made once the prices of all components are known, both direct and indirect subsidies perform equally and can be applied. In this case, given the low cost difference between the two technologies, one of the firms will adopt the superior technology without policy intervention. In addition, when the impact of the externality becomes relatively more important than the production cost difference, all firms in the market should be given subsidies.

3.6 Extension: compatibility between S- and E-based components

This section introduces compatibility between system good components based on different technological standards. The parameter of compatibility is introduced as a discrete value $\beta \in \{0, 1\}$ in the denominator of the transportation cost related to the distance of consumers to the available variety of component B. If $\beta = 0$ we obtain the model presented in Section 2, where only U^{SS} and U^{EE} are relevant for consumers' choices. With compatibility between different standards ($\beta = 1$), the consumers' utility from using the system composed of an S-based component A and an E-based component B is given by $U^{SE} = U_0 - p^{AS} - a^2t - p^{BE} - \left(\frac{1}{2} - b\right)^2 t$. Analogically, consumers' utility from the system composed of an E-based component A and an S-based component B is given by $U^{ES} = U_0 - p^{AE} - (1-a)^2 t - p^{BS} - b^2 t$.

The timing of the game is similar to that in Sections 3 and 5 independently of whether consumers commit or not to the technological standard in stage 3. Firms compete between them in markets A and B independently of the market for the complementary component.

As in Section 2, the established standard has a negative externality. If a system good consists of two E-based components, the cost of the externality is quadratic in the total quantity of E-based system goods with damage function is $\varepsilon \left(\sum_{i=1,2} D_i^E\right)^2 /2$, $\varepsilon > 0$. If the system good consists of an S- and an E-based component, it is assumed that only half of the system good generates a negative externality, such that the damage function is $\varepsilon \left(\sum_{i=1,2} D_i^{SE}/2\right)^2 /2$. For instance, a hybrid car generates fewer emissions than an internal combustion car. Social welfare W is defined as the sum of consumers' surplus in the two markets, firms' profits and externality costs.

In stage 4, the prices of firms in market B are derived similarly as in the basic model. If both firms in market B choose the same technological standard the prices are determined by profit maximization as $p^{Bk} = c^{Bk} + t/4$. If firms in market B choose different standards, the prices are the same as in 79.

Due to perfect compatibility between all components, the consumer choice of component A in stage 3 does not depend on the technological standards chosen by the firms in market B. The demand of S- and E-based components in market A is determined by the location of the consumer indifferent between the S- and E-based component A. From $U^{SS} = U^{ES}$ and $U^{SE} = U^{EE}$ we obtain her location as:

$$a = \frac{1}{2t}\left(p^{AE} - p^{AS} + t\right) \tag{105}$$

Provided that the choice of component A does not determine the market share of S- and E-based systems, the demand of firms in market B is only affected by their strategic interaction. The consumer indifferent between S- and E-based components B is situated at $b = -\delta/3t + 1/4$, therefore, the equilibrium demand of firm 1 is $D_1^S = 2b$ and that of firm 2 is $D_2^E = 1 - 2b$. In stage 2, firms in market B choose technological standards. Three possible scenarios are represented in 10. If both firms in market B choose standard S, i.e. locate at $a = 0$, the system goods available are S,S and E,S.

The market shares of an S-based system good and an ES-based system good are 1/2. If both firms in market B choose standard E, i.e. locate at $a = 1$, the market shares of an E-based and an SE-based system goods are 1/2, too. Then, stage 3 equilibrium profits are the same as in (78). Finally, if one firm in market B chooses an S-based technological standard and the other firm chooses an E-based technological standard, stage 3 equilibrium profits are given by

$$\begin{aligned} \Pi_1^S(S,E) &= \frac{(3t-4\delta)^2}{72t} - F \\ \Pi_2^E(S,E) &= \frac{(3t+4\delta)^2}{72t} - F \end{aligned} \tag{106}$$

Because $\Pi_1^S(S,E) < \Pi_1^E(E,E)$ and $\Pi_2^S(S,S) < \Pi_2^E(E,S)$ the firms in market B have no incentive to adopt a superior technology without policy intervention. However, consumers that are located in the neighbourhood of S in market A will now choose the S-based component A for any location with respect to component B. Therefore, with compatibility between the components, the negative externality imposed on society will be lower.

The implementation of indirect and direct subsidies affects consumers choices differently. Regarding the indirect subsidy, it affects adoption behaviour only in market A. With the indirect subsidy, as in the basic framework, the price for S-based component A is given by $p^{AS} = c^A - s^A$. This increases the share of consumers of S-based component A to

$$a = \frac{1}{2} + \frac{s^A}{2t}. \tag{107}$$

Although, in the case of perfect compatibility the indirect subsidies have no effect on demand and, consequently, profits and technological standard choices of firms in market B, they affect the consumers' choice regarding the component A increasing the market share of an S-based component A. Thus, a negative externality is diminished. Because firms B' strategies are not affected by indirect subsidies, the only possible equilibrium will be the one in which both firms in market B choose technological standard E. Then, the social welfare is given by:

$$\begin{aligned} W^A(E,E) &= 2A\int_0^{\frac{1}{4}}\int_0^{a^A}\left(U_0 - p^{AS} - p^{BE} - x^2t - y^2t\right)dxdy \\ &+2A\int_0^{\frac{1}{4}}\int_{a^A}^{1}\left(U_0 - p^{AE} - p^{BE} - (1-x)^2t - y^2t\right)dxdy \\ &+2\Pi_i^{BE}(E,E) - \frac{\varepsilon}{2}\left(D^{EE}\right)^2 - \frac{\varepsilon}{2}\left(\frac{D^{SE}}{2}\right)^2 - s^A D^{SE} \end{aligned}$$

Deriving the welfare maximizing indirect subsidy we obtain the following result:

Lemma 6. *The optimal indirect subsidy to firms in market A is* $s^A = \frac{3t\varepsilon}{8t+5\varepsilon}$.

In the case of direct subsidies, if both firms in market B choose standard S, their prices are $p_i^{BS} = c_1^{BS} - s^B + t/4$ and profits are equal to (78). If one firm choose standard S and another firm chooses standard E, the prices in market B are the same as in (93). Now direct subsidies affect also the demands of firms in market B. The market share of an S-based component B is given by $b = \frac{s^B}{3t} - \frac{\delta}{3t} + \frac{1}{4}$ and the market share of an E-based component B is $\frac{1}{2} - b = \frac{\delta - s^B}{3t} + \frac{1}{4}$. Then, firms' profits are

$$\begin{aligned} \Pi_1^S(S,E) &= \frac{\left(3t - 4\delta + 4s^B\right)^2}{72t} - F \\ \Pi_2^E(S,E) &= \frac{\left(3t + 4\delta - 4s^B\right)^2}{72t} - F \end{aligned} \tag{108}$$

Comparing the payoffs of firms in market B with direct subsidies we obtain the following result.

Lemma 7. *Given an E-based firm in market B, its rival adopts a superior standard S, if it gets a subsidy* $s \geq \underline{s}_1^B \equiv \delta$. *Similarly, given an S-based firm in market B, its rival adopts a superior standard S if it gets a subsidy* $s \geq \underline{s}_2^B \equiv \delta$.

Proof. Analogically to Proof of Lemma 5.

Given equilibria of the model the analysis of social welfare with compatibility yields the following result.

Proposition 5. In the presence of perfect compatibility between technologies the optimal policy intervention is determined by the following optimal subsidies:

$$(s_1, s_2) = \begin{cases} (0,0) & \text{for} \quad 0 < \varepsilon/t \leq \epsilon_{10} \text{ and } 0 < \varepsilon/t \leq \epsilon_{11} \quad \text{(Region 1)} \\ \left\{s^A_{\max}\right\} & \text{for} \quad \epsilon_{11} < \varepsilon/t \leq \epsilon_{12} \quad \text{(Region 2A)} \\ \left(\underline{s}^B_1, \underline{s}^B_2\right) & \text{for} \quad \epsilon_{10} < \varepsilon/t \text{ and } \epsilon_{12} < \varepsilon/t \quad \text{(Region 3B)} \end{cases}$$

where $\epsilon_{10} = 8\,(\delta/t)$, $\epsilon_{11} = \frac{5+\sqrt{889}}{54}$ and $\epsilon_{12} = \frac{80}{11}\,(\delta/t) + \frac{1}{66}\sqrt{230\,400\,(\delta/t)^2 + 4416\,(\delta/t) + 9145} - \frac{101}{66}$.

Proof. In the Appendix.

The regions different regions are displayed in Figure 11. With perfect compatibility between components based on different technological standards the indirect subsidies gain advantage in comparison to direct subsidies if both the externality cost and the production cost difference between the two standards are high (Region 2A). Direct subsidies are optimal if the externality cost is high but the cost difference between the established and the superior technology is low (in Region 3B). Even in the presence of perfect compatibility the result that all technology adopters should be given direct subsidies provided a high externality cost is confirmed.

3.7 Concluding remarks

This paper addresses optimal subsidy choice in the context of markets with complementary goods in the presence of externalities. Subsidies are aimed at enhancing firms' incentives for transition from an established technological standard, which is cheaper but causes a negative externality, to a superior standard. We show that once there is an established technological standard, without policy intervention, firms have no incentives to adopt a superior standard. The policy instruments analyzed are indirect and direct subsidies. The conditions for optimal subsidies are indicated depending on the cost difference between standards, the impact of the externality and the presence of consumers' "commitment" to a determined technology. If consumers' purchasing decision is made before the prices of one of the components of the system good are known, policy intervention is desirable only when the impact of the externality is not lower than the cost difference between standards. Then, if the impact of the externality is relatively similar to the cost difference between standards, it is optimal to give a direct subsidy to provide incentives for the transition to the superior standard only to the first technology adopter. Furthermore, the higher the externality becomes, the more technology adopters must be targeted with subsidies. This means that in case of direct subsidies, both technology adopters should be given a direct cost-reducing subsidy per unit of production using the superior standard. In case of indirect subsidies, the necessary amount of cost-reducing subsidies should be given to the producers of the complementary component per volume of production using the superior standard. The comparison between direct and indirect subsidies suggests that when the cost difference between technological standards is high and the externality is low or intermediate, direct subsidies are socially preferable. When the externality cost is high and the cost difference is low, direct and indirect subsidies perform equally. However, because the optimal indirect subsidy is higher than the direct subsidy, the direct subsidy leads to higher social welfare. If consumers' purchasing decision is made after the prices of all components of the system good are known (i.e. in the absence of "commitment"), the effects of indirect and direct subsidies' are equal. In this case, if the production cost difference is low the first adopter might have natural incentives to adopt the superior technology. This means that the adoption of the superior technology implies a lower cost for society. If the production cost difference is high, the adoption requires direct or indirect subsidies. Moreover, the subsidy to the second adopter is higher than the subsidy to the first adopter. Finally, compatibility between components based on different technological standards enhances an advantage of indirect subsidies for the case of a high externality cost and a high cost difference between the established and the superior technological standard.

Regarding the before mentioned policy examples of Brazil and of the US the results have some interesting implications. In Brazil, as a result of indirect subsidies implementation, by the year 1990, 90% of vehicle manufactures in Brazil used technology allowing to power vehicles by alcohol. According to our results, this technology adoption policy is more costly for society in the presence of consumers' "stickiness" to technology, i.e., if consumers are a priori restricted to use the superior or the established technology. In this case indirect subsidies are less efficient because at the beginning of new car technology adoption, consumers by choosing a car are conditioned by the availability of all related infrastructure in their urban area (charging and service stations, parking area). On the contrary, when the infrastructure for both technologies is installed and consumers can make their purchasing decision after the prices for all components are known, both subsidies perform equally. In the US, direct subsidies to car manufacturers were chosen. According to our results, this is the optimal solution at the beginning of superior technology adoption. However, once the infrastructure for both technologies is installed (in other words, in the absence of consumers' "stickiness" to technology), indirect subsidies to producers of clean energy technologies (biofuels, electricity generation) should also be implemented.

The results have been discussed in the context of optimal subsidy choice to enhance environmental performance in the markets for system goods. However, these results provide a rationale for a wide range of policies. A similar problem of technology adoption arises in industries related to national defense. The systems' components are produced by a number of public and private firms. Usually, public companies elaborate the basic architecture of the system (hardware), while some of the components are provided by external private firms. In this interaction private firms need incentives for transition to a new technology. For instance, satellite navigation services are enabled by equipment of GPS. Many private firms provide a number of applications using the GPS signal. Therefore, nowadays, the world market for satellite navigation is dominated by GPS, which is under military control of the US. For the European economy this sector has become very important (about 7% of the EU GDP in 2009) and is expected to grow. Therefore, in order to provide Europe independence in satellite navigation, the Galileo project was launched. The use of Galileo generates a number of positive externalities for security and economic reasons. Therefore, the national government aiming to promote a national GNS must provide incentives to the producers of services to switch to the national technological standard, for instance, to substitute GPS chipsets by Galileo ones in cell phones. This might raise costs as further development of devices and applications is needed to explore higher precision possibilities of Galileo. Two approaches to provide firms with incentives for R&D collaboration can be applied. First, the contract between public entity and private firms can be improved to make more favorable conditions than with GPS. Second, direct subsidies can be given to private firms to adopt Galileo. In order to choose between the two policies, the positive externalities, the cost difference between the two technologies and the effect of consumers "commitment" should be considered. The "less optimistic" estimates taking account of the possible impacts of the economic crisis suggest that the total accumulated benefits coming from Galileo over the period 2008-2030 would be between €55 and €62b. The consumers of GNS-based applications can be committed to the use of national system by political means. In this case, because the positive externality is estimated as very high, and the cost difference is relatively small, our results suggest that it would be socially optimal to subsidize firms that produce Galileo-based instead of GPS-based applications, i.e. to use a direct subsidy.

3.8 Appendix

3.8.1 Proof of Proposition 1

First, consider the situation that both firms adopt standard E. Then, $s^A = 0$ and welfare is:

$$W^A(E,E) = U_0 - c^A - c^{BE} - 2F - \frac{17}{48}t - \frac{\varepsilon}{2}. \tag{109}$$

Second, if firms in market A receive subsidies $s^A = s_1^A$, both firms in market B adopt standard S, and welfare is:

$$W^A(S,S) = U_0 - c^A - c^{BE} - 2F - \frac{17}{48}t - \delta. \tag{110}$$

These subsidies are sufficient to make both firms adopt standard S.

Finally, to determine the optimal policy, we must compare social welfare in expressions (109) and (110). We get:

$$W^A(S,S) - W^A(E,E) > 0 \quad \text{for} \quad \epsilon_1 < \varepsilon/t, \tag{111}$$

where $\epsilon_1 = 2(\delta/t)$ and $\delta/t < 9/28$. This expression determines the intervals for subsidies in market A, which are given in Proposition 1 and displayed in Figure 6.

3.8.2 Proof of Proposition 2

First, consider the optimal subsidy to firm 1 that maximizes $W^B(S,E)$. Substituting $p^{AS} = p^{AE} = c^A$, the prices in (93), equation (94), profits from (96) and (97) and demands from (**??**) into (100), after some calculations we get:

$$\max_{s^B > \underline{s}^B} W^B(S;E) = U_0 - c^A - c^{BE} - 2F - \frac{16s(s+t+4\delta) + 272t\delta - 80\delta^2 + 57t^2}{576t} - \frac{\varepsilon}{72}\left(\frac{3t+\delta-s}{t}\right)^2. \tag{112}$$

The welfare maximizing subsidy is $s_{\max}^B = \frac{(3t+\delta)\varepsilon - 4t\delta - t^2}{2t+\varepsilon}$. This subsidy must fulfill the restriction $s_{\max}^B \geq \underline{s}_1^B$ to provide sufficient incentives to firm 1 to adopt the standard S. This is:

$$\left(s_1^B, s_2^B\right) = \begin{cases} (\underline{s}_1^B, 0) & \text{for} \quad (\varepsilon/t) \leq \epsilon_3 \\ (s_{\max}^B, 0) & \text{for} \quad (\varepsilon/t) > \epsilon_3 \end{cases}, \tag{113}$$

where $\epsilon_3 = 2(\delta/t) + 1/3$. Consequently, we have:

$$W^B(S;E) = \begin{cases} U_0 - c^A - c^{BE} - 2F - \frac{19t+96\delta+24\varepsilon}{192} & \text{for} \quad (\varepsilon/t) \leq \epsilon_3 \\ U_0 - c^A - c^{BE} - 2F - \frac{2\left(240t\delta - 144\delta^2 + 53t^2\right) + 3\varepsilon(83t+192\delta)}{576(2t+\varepsilon)} & \text{for} \quad (\varepsilon/t) > \epsilon_3 \end{cases}. \tag{114}$$

Second, consider the situation that both firms adopt standard E. Then, $\left(s_1^B, s_2^B\right) = (0,0)$ and welfare is:

$$W^B(E;E) = U_0 - c^A - c^{BE} - 2F - \frac{17}{48}t - \frac{\varepsilon}{2}. \tag{115}$$

Third, if firms in market B receive subsidies $\left(s_1^B, s_2^B\right) = (\underline{s}_1^B, \underline{s}_2^B)$, both firms adopt standard S, and welfare is:

$$W^B(S;S) = U_0 - c^A - c^{BE} - 2F - \frac{17}{48}t - \delta. \tag{116}$$

Therefore, these subsidies are sufficient to make both firms adopt standard S.

Finally, to determine the optimal policy, we must compare social welfare in expressions (114)-(116). From (114) and (115) we get:

$$W^B(S;E) - W^B(E;E) > 0 \quad \text{for} \quad \epsilon_2 < \varepsilon/t \leq \epsilon_3, \tag{117}$$

where $\epsilon_2 = \frac{4}{3}(\delta/t) - \frac{49}{72}$ and $\epsilon_3 = 2(\delta/t) + \frac{1}{3}$. From (114) and (116) we get:

$$W^B(S;E) - W^B(S;S) > 0 \quad \text{for} \quad \epsilon_3 < \varepsilon/t \leq \epsilon_4 \text{ and } \varepsilon/t \leq \epsilon_5, \tag{118}$$

where $\epsilon_4 = \frac{32}{5}(\delta/t)^2 + \frac{224}{15}(\delta/t) + \frac{302}{45}$ and $\epsilon_5 = 8(\delta/t) + \frac{22}{3}$. Together, these expressions determine the intervals for subsidies in market B that are given in Proposition 2 and displayed in Figure 7.

$$\left(s_1^B, s_2^B\right) = \begin{cases} (0,0) & \text{for} \quad 0 < \varepsilon/t \leq \epsilon_2 & \text{(Region I)} \\ (\underline{s}_1^B, 0) & \text{for} \quad \epsilon_2 < \varepsilon/t \leq \epsilon_3 & \text{(Region II')} \\ (s_{\max}^B, 0) & \text{for} \quad \epsilon_3 < \varepsilon/t \leq \epsilon_4 \text{ and } \varepsilon/t \leq \epsilon_5 & \text{(Region II")} \\ (\underline{s}_1^B, \underline{s}_2^B) & \text{for} \quad \epsilon_4 < \varepsilon/t & \text{(Region III)} \end{cases}$$

where $s_{\max}^B = \frac{(3t+\delta)\varepsilon - 4t\delta - t^2}{2t+\varepsilon}$.

3.8.3 Proof of Proposition 3

If indirect subsidies are given to firms in market A this yields social welfare:

$$W^A = \begin{cases} U_0 - c^A - c^{BE} - 2F - \frac{17}{48}t - \frac{\varepsilon}{2} & 0 \leq \varepsilon/t \leq \epsilon_1 & \text{(Region I)} \\ U_0 - c^A - c^{BE} - 2F - \frac{17}{48}t - \delta & \epsilon_1 < \varepsilon/t & \text{(Region III)} \end{cases}.$$

If direct subsidies are given to firms in market A this yields social welfare:

$$W^B = \begin{cases} U_0 - c^A - c^{BE} - 2F - \frac{17}{48}t - \frac{\varepsilon}{2} & \text{for} \quad 0 < \varepsilon/t \leq \epsilon_2 & \text{(Region I)} \\ U_0 - c^A - c^{BE} - 2F - \frac{19t+96\delta+24\varepsilon}{192} & \text{for} \quad \epsilon_2 < \varepsilon/t \leq \epsilon_3 & \text{(Region II')} \\ \begin{array}{l} U_0 - c^A - c^{BE} - 2F - \\ \frac{2\left(240t\delta - 144\delta^2 + 53t^2\right) + 3\varepsilon(83t+192\delta)}{576(2t+\varepsilon)} \end{array} & \text{for} \quad \begin{array}{l} \epsilon_3 < \varepsilon/t \leq \epsilon_4 \\ \text{and } \varepsilon/t \leq \epsilon_5 \end{array} & \text{(Region II'')} \\ U_0 - c^A - c^{BE} - 2F - \frac{17}{48}t - \delta & \text{for} \quad \epsilon_4 < \varepsilon/t & \text{(Region III)} \end{cases}.$$

Comparing social welfare in each region, we choose between subsidies to S-based firms in markets A and B that lead to higher social welfare:

$$W^{A,B} = \begin{cases} W^B > W^A & \text{for} \quad \epsilon_2 < \varepsilon/t \leq \epsilon_3 & \text{(Region 2)} \\ W^B > W^A & \text{for} \quad \epsilon_3 < \varepsilon/t \leq \epsilon_4 \text{ and } \varepsilon/t \leq \epsilon_5 & \text{(Region 3)} \\ W^A = W^B & \text{for} \quad \epsilon_4 < \varepsilon/t & \text{(Region 4)} \end{cases},$$

where $\delta/t < 9/28$.

3.8.4 Proof of Proposition 4

If indirect or direct subsidies are given to firms in market A or B this yields social welfare:

$$W^{A,B} = \begin{cases} U_0 - c^A - c^{BE} - 2F - \delta - \frac{17}{48}t & \text{for} \quad 0 < \varepsilon/t \leq \epsilon_7 \text{ and } 0 < \delta/t \leq 3/2 & \text{(Region 1a)} \\ U_0 - c^A - c^{BE} - 2F - \delta - \frac{17}{48}t & \text{for} \quad 0 < \varepsilon/t \leq \epsilon_8 \text{ and } 3/2 < \delta/t \leq 9/4 & \text{(Region 1b)} \\ U_0 - c^A - c^{BE} - 2F - \frac{23t+48\delta+54\varepsilon}{192} & \text{for} \quad \epsilon_8 < \varepsilon/t \leq \epsilon_9 \text{ and } 3/2 < \delta/t \leq 9/4 & \text{(Region 2a)} \\ \begin{array}{l} U_0 - c^A - c^{BE} - 2F \\ -\frac{1}{576}\frac{480t\delta+249t\varepsilon-288\delta^2+576\delta\varepsilon+106t^2}{2t+\varepsilon} \end{array} & \text{for} \quad \begin{array}{l} \epsilon_9 < \varepsilon/t \leq \epsilon_{10} \\ \text{and } 3/2 < \delta/t \leq 9/4 \end{array} & \text{(Region 2b)} \\ U_0 - c^A - c^{BE} - 2F - \delta - \frac{17}{48}t & \text{for} \quad \epsilon_7 < \varepsilon/t \text{ and } 0 < \delta/t \leq 3/2 & \text{(Region 3a)} \\ U_0 - c^A - c^{BE} - 2F - \delta - \frac{17}{48}t & \text{for} \quad \epsilon_{10} < \varepsilon/t \text{ and } 3/2 < \delta/t \leq 9/4 & \text{(Region 3b)} \end{cases}.$$

Comparing social welfare we find the frontiers between Regions.

3.8.5 Proof of Proposition 5

If indirect or direct subsidies are given to firms in market A or B this yields social welfare:

$$W^{A,B} = \begin{cases} U_0 - c^A - c^{BE} - 2F - \frac{3}{32}t - \frac{5}{32}\varepsilon & \text{for} \quad 0 < \varepsilon/t \leq \epsilon_{10} \text{ and } 0 < \varepsilon/t \leq \epsilon_{11} & \text{(Region 1)} \\ U_0 - c^{BE} - c^A - 2F - \frac{1}{48}\frac{85t\varepsilon+24\varepsilon^2+40t^2}{8t+5\varepsilon} & \text{for} \quad \epsilon_{11} < \varepsilon/t \leq \epsilon_{12} & \text{(Region 2A)} \\ U_0 - c^A - c^{BE} - 2F - \delta - \frac{3}{32}t - \frac{1}{32}\varepsilon & \text{for} \quad \epsilon_{10} < \varepsilon/t \text{ and } \epsilon_{12} < \varepsilon/t & \text{(Region 3B)} \end{cases}.$$

Comparing social welfare we find the frontiers between Regions.

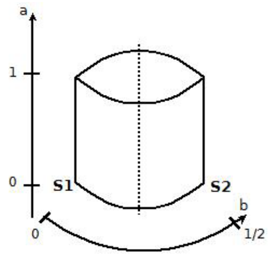

Figure 5: The structure of a market for system goods. The dashed line shows how the market is divided between producers of S- and E-based system goods.

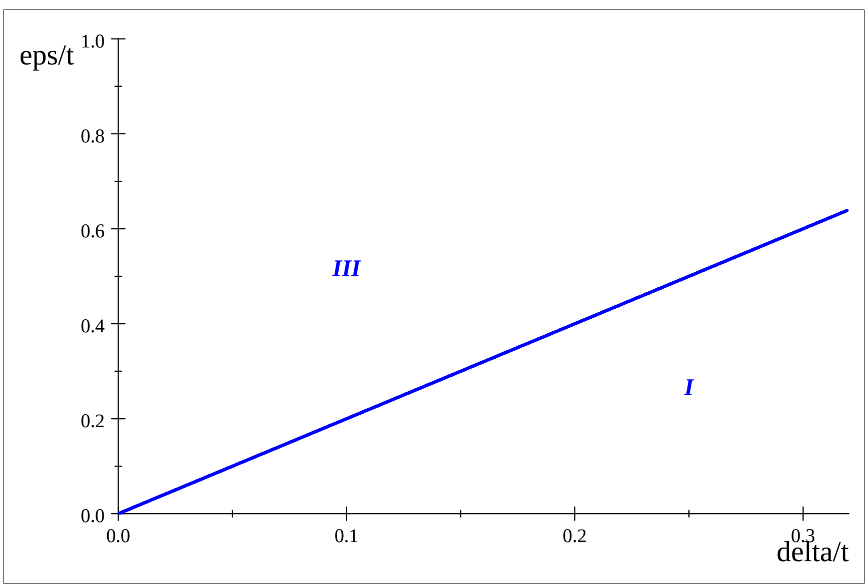

Figure 6: The four regions for optimal subsidies in market A for the superior technology adoption.

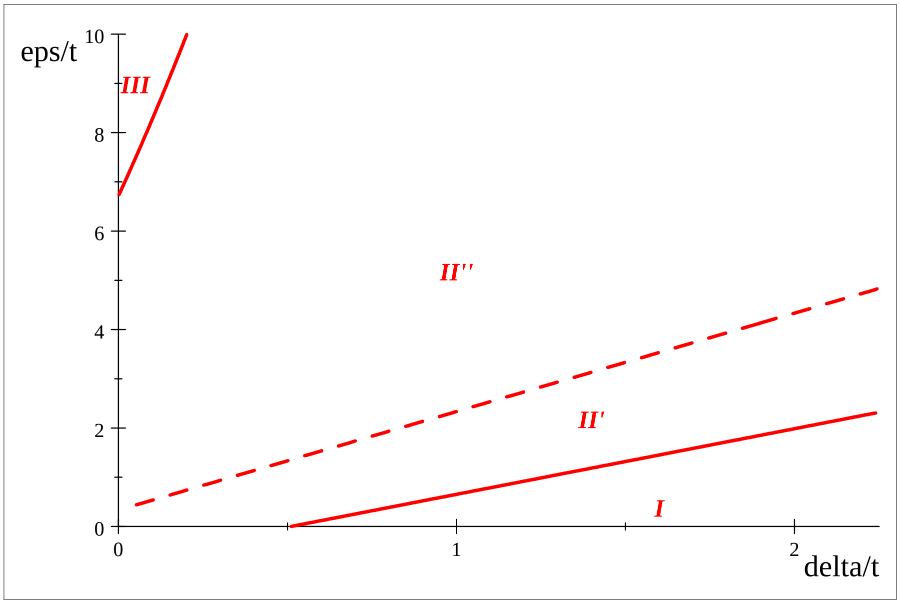

Figure 7: The four regions for optimal subsidies in market A for the superior technology adoption.

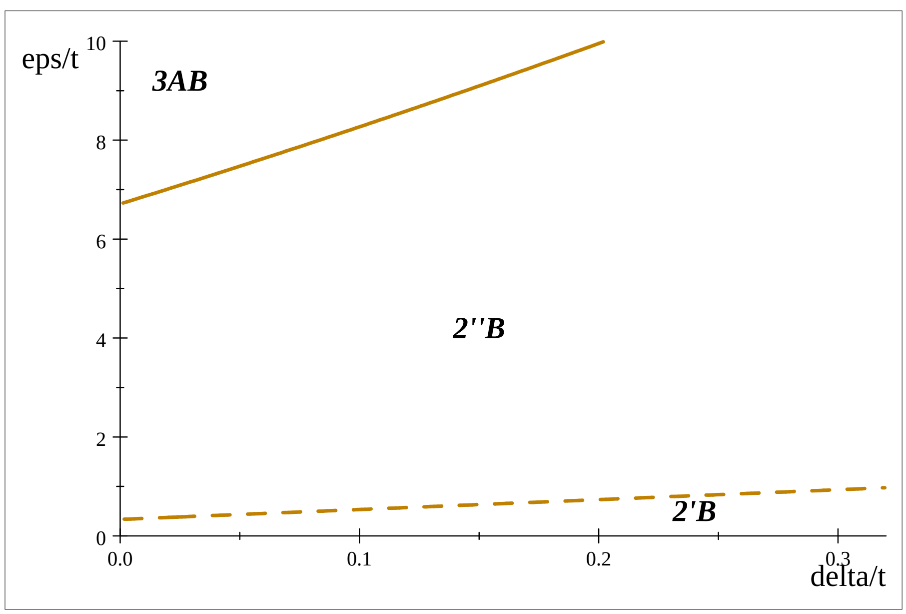

Figure 8: The three regions for optimal policy interventions in markets A and B.

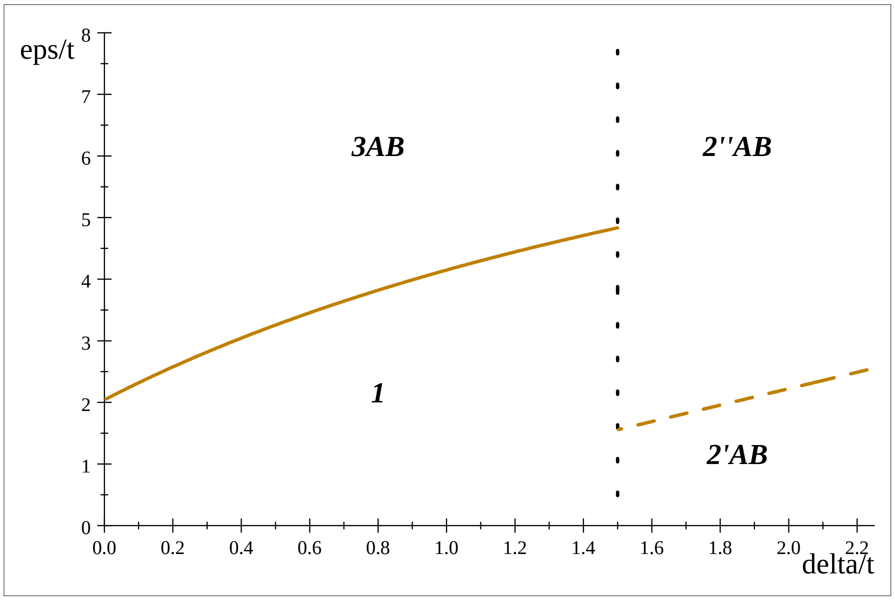

Figure 9: The five regions for optimal policy interventions in markets A and B.

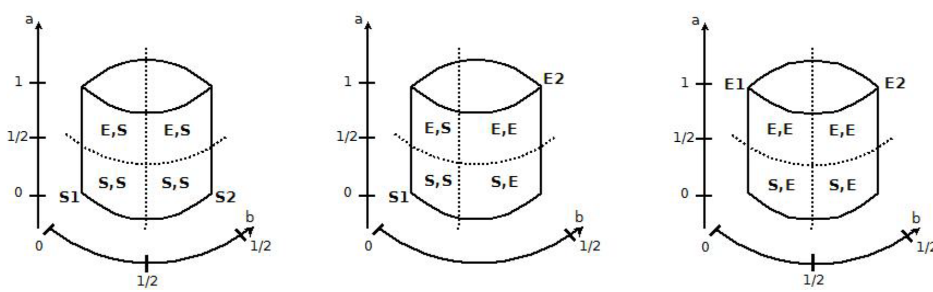

Figure 10: The structure of a market for system goods in the case of perfect compatibility between S- and E-based components. The dashed line shows how the market is divided between different system goods.

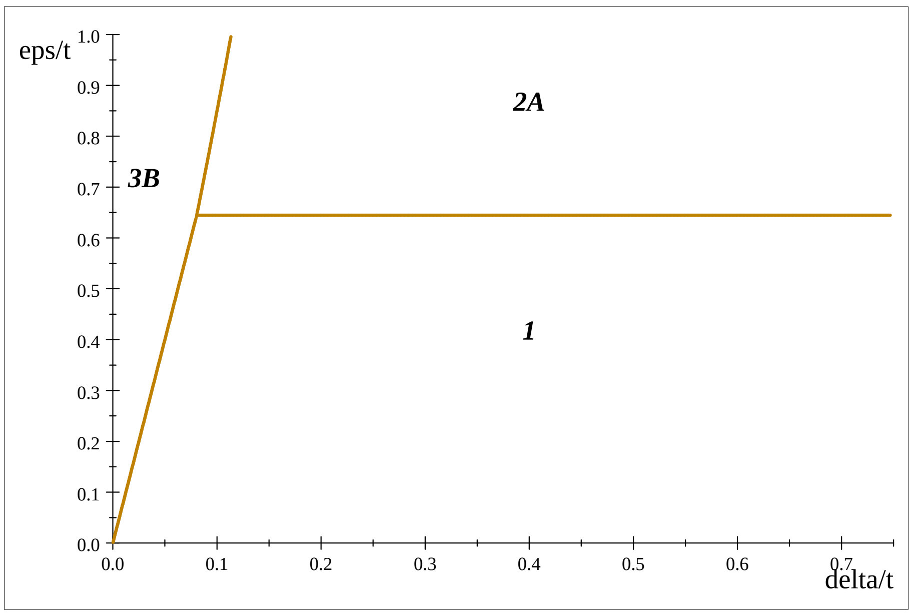

Figure 11: The four regions for optimal policy interventions in markets A and B with perfect compatibility.

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