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Abstract

In the recent last years, in particular in the aftermath of the global financial and economic crisis, many countries initiated economic recovery plans with a major focus on stimulating green entrepreneurial activities to revive economic growth. Further, the recovery plans intend to improve a country's awareness for a direct orientation towards (strong) sustainability and green growth. Before discussing strategies towards green growth, in this paper we propose a novel framework to increase our understanding of the interplay of process R&D activities, the strategic price and environmental quality setting of heterogeneous entrepreneurs in a market where consumers feel up to paying for environmental quality improvement of a vertically differentiated good. In the paper we decompose an entrepreneur's incentive conducting process R&D in four parts. In particular we show that an entrepreneur's incentive of conducting own process R&D is reduced due to the existence of knowledge-spillovers. Moreover, due to the strategic complementarities, both in prices as well as in environmental quality, a strategic effect reinforces the negative consequences of the spillover-effect. We show that the externalities in the model require corrections based upon a mixture of fiscal policies and a process R&D subvention scheme establishing a first-best solution. We further thoroughly discuss the implementation of a second-best solution and derive environmental policy implications.

1 Introduction

Products claiming to be environmentally friendly or green are on the rise as consumer's environmental conscience perceivably increases over the last decade. According to the recently published GfK Roper Yale Survey on Environmental Issues, the majority of the US-American and Canadian citizens argue that product purchases should be eco-friendly (GfK (2008)). Although the market share of green products and related services in the United States remains small in the past (1%-2% in 2007)[1], according to a recent analysis conducted by the US Department of Commerce impressively reveals that this sector is steadily growing in all green product segments (US Department of Commerce (2010)). For instance, in 2008, US organic food sales grew by approximately 16% and reached a volume of 22.9 billion US dollar (Organic Trade Association (2009)). A qualitatively similar pattern can be obtained for Canada by contrasting US and Canadian food sales data (Bowles (2011)). By reflecting recently published European Commission surveys for the years 2008 and 2009, nearly 75% (2005: 31%) of all Europeans would buy environmentally-friendly (European Commission (2008) and European Commission (2009)) and reading the afore mentioned surveys carefully, consumers seem to be even prepared to pay a price premium for environmentally-friendly products (Bowles (2011), European Commission (2008) and European Commission (2009)). The soaring importance of green growth can be also observed in China: the 12th Five Year Plan particularly emphasizes the increasing importance of *going green* for China's economic growth (Casey and Koleski (2011)).

The global relevance of the green sector can be also fleshed out in the context of the recent financial and economic crisis. Although the priorities investing in environmentally friendly products or services are not new, it seems that particularly in the aftermath of the recent economic and financial crisis, there seems to be a forum for a revitalized and more thorough discussion of identifying drivers for sustainable economic growth. As pointed out by the OECD (2011), in particular fostering green entrepreneurship[2] seems to be one of the promising key boosting economic activities as nearly 99% of all OECD countries' firms (OECD-WPSMEE (2010)) belong to the small and medium-

[1] Refer to the survey published by the US Department of Commerce (2010).

[2] In this paper we follow Isaak (2005) and assume that an entrepreneur acts in a green sector of an economy with a strong commitment towards sustainability. For a detailed description of the characteristics of a green sector please refer to OECD/Eurostat (1999) definition.

sized (SME) sector[3] and it is expected that green innovations can be particularly traced back to young firms (OECD-WPSMEE (2010)). Further, by referring to the various fiscal stimulus packages initiated by most of the economically leading countries in response to the global economic and financial crisis, we observe that these are to some degree designed for encouraging growth on sustainable grounds. For instance, China's administration has devoted almost 40% of its fiscal stimulus package of USD 586 billion to foster Chinas' green investments (Girouard (2010)), which also comprises process R&D investments into energy technologies, and funds to improve firms' production infrastructure (Hammer et al. (2011)). In 2009, South Korea invested 79% of its stimulus package in the green sector, which nearly accounts for 7% of its GDP.[4] For the United States, it is expected that the USD 90 billion Recovery Act accounts for nearly 720,000 jobs to be created or saved (OECD-WPSMEE (2010)), whereas green funds in the European Union accounts for 8.5% of the total stimulus funds (HSBC Global Research (2009)). Hence "[...] the study of green entrepreneurship went from being simply "fashionable" to being essential for policy guidance. [...]"[5].

As pointed out by (OECD-WPSMEE (2010)), before discussing new strategies towards green growth, we first have to increase our understanding regarding the interplay of sustainable production of green products and services, the market structure and the management practices of production processes of green entrepreneurs, which defines the core of this contribution. As it seems to be a challenging task to separate green entrepreneurship from entrepreneurship (OECD (2011)), unambiguously the question arises how entrepreneurs who are heterogeneous with respect to their environmental product quality compete in a market where, based on the above stated empirical evidence, consumers obviously are prepared to pay for environmental quality of a product which is vertically differentiated in environmental quality.

Commonly, it is assumed that entrepreneurs via *creative destruction*[6] are able to either improve their production processes or to improve their product quality or both. Green

[3]Entrepreneurship and SME's are closely related (Audretsch 2007). Although there exists no clear cut definition how to characterize concisely a SME, nevertheless, Acs and Audretsch (1988) define SMEs as firms with less than 500 employees.

[4]See United Nations Environmental Program UNEP (2009).

[5]Refer to part I, chapter 2, p.24, OECD (2011).

[6]This well established notion of an entrepreneur comprises his *creative destruction* function which can be traced back to Schumpeter (1934): the inherent dynamics induced by innovations due to R&D endeavors will replace existing and inferior technologies by new and superior technologies and, hence, enhances growth.

or not, to cope with the specific attributes directly associated with an entrepreneur, for instance the creation of new innovative products, services and processes, *ex-ante* we have to define an entrepreneur's technology strategy, which can result either in a product or a process innovation (Vaona and Pianta (2008))[7]. Whereas product innovations are assumed to directly emerge from the result of technological competitiveness with respect to product development, process innovations which scope seems to be broader, are directly associated with a strategy of searching for new or more efficient (production) technologies, as the investment in more efficient machineries (Antonucci and Pianta (2002), Pianta (2001)) and the improvement of management operations and/or organizational change in firms[8]. With respect to the above mentioned literature[9], it seems to be appropriate primarily to focus on process innovations[10].

In a nutshell, the core of the paper is twofold: first, we develop a three-stage model discussing the interplay of conducting process R&D activities and the price and environmental quality setting behavior of heterogeneous entrepreneurs in a market where consumers are willing to pay a price premium for environmental's quality improvement

[7]This assumption is based on a well-established literature. For instance, refer to Antonucci and Pianta (2002), Cohen and Klepper (1994), Edquist, Hommen and McKelvey (2001), Pianta (2001) and Scherer (1991).

[8]We inherently assume that entrepreneurs to some extent are not restricted to conducting R&D. However, this is a simplification of reality. For instance, one crucial barrier for entrepreneurial activities are financial restrictions such as credit constraints. Although important and object of current research (for a comprehensive discussion regarding this issue refer to Antony, Maußner and Klarl (2012)), we neglect this issue as our primary focus is not directly related towards a discussion of the presence of credit constraints and its implications for green growth driven by entrepreneurial activities. As clearly beyond the scope of this contribution, we leave this discussion open as an avenue for further research.

[9]In particular, we follow (OECD-WPSMEE (2010)).

[10]Vaona and Pianta (2008) evaluating a rich manufacturing firm's panel-data set for eight European countries (Austria, France, Italy, Norway, the Netherlands, Portugal, Sweden, and the United Kingdom) on a sectorial level, conclude that firm size does not play a decisive role in identifying determinants for conducting either process or product innovations. This result is in contrast to earlier findings: Scherer (1991), for instance, concludes that the share of process innovations relative to product innovations increases with firm size. In this article we assume that entrepreneurs which are closely associated with SMEs (Audretsch (2007)) conducting process innovations. Nevertheless, it is worth mentioning that there exists a large literature regarding the innovative power of smaller and larger firms without directly focusing on product and process innovations. Cohen and Klepper (1996) and Scherer (1965) by investigating the link between firm size and innovation activities, found that larger firms are more innovative than smaller ones. Whereas the afore mentioned two studies concentrate on R&D inputs, Acs and Audretsch (1990) and Acs and Audretsch (1991) found by directly linking the R&D activity with patent activity that smaller firms are more innovative.

of a vertically differentiated good. Second, based on the models' results, we compare the welfare-implications for a regulated and unregulated economy with the social planer solution, when the governmental authority's aim is to correct for arising externalities stemming from the entrepreneur's market power – resulting, as shown, in excessive product-differentiation as well as in excessive environmental damage – and occurring process R&D spillovers. Before we introduce the setting of the model, the next section deals with a short review of the relevant literature to which the model is directly related.

2 Related Literature

By referring to our research question motivated in the first chapter of this paper, we can identify two major strands of literature which we combine in this paper. The first embeds the environmental quality of a product into existing models of vertical product differentiation in the spirit of Mussa and Rosen (1978), Cremer and Thisse (1994) and Cremer and Thisse (1999). Following Lombardini-Riipinen (2005), Brécard (2008) and Brécard (2012) we assume that the considered product market is vertically differentiated in environmental quality. Although it seems that the majority of US consumers base their purchase decision primarily on prices and not on environmental quality, several studies conducted by the European Commission (2008) and the European Commission (2009) clearly state that it seems that consumers are willing to pay a price premium for green products.

The model presented in this contribution is closest related to Lombardini-Riipinen (2005), Brécard (2008) and Brécard (2012). Lombardini-Riipinen (2005) thoroughly study the welfare-implications of an emission and *ad-valorem* tax in a market of vertically-differentiated products with respect to environmental quality, embedded into a two-step-game. Assuming full market coverage, quality is strictly increasing marginal production costs and a representative consumer buys one product or nothing, Lombardini-Riipinen (2005) found that the first-best optimum of product-quality can be obtained by a combination of an *ad-valorem* and imposed emission tax. If the policy-maker can only set the environmental tax, the second-best policy is imposing the Pigouvian tax. Brécard (2012) extends the analysis of Lombardini-Riipinen (2005) by explicitly introducing green network effects, as many purchase decision are influenced by social ties.[11] As prices and produced qualities are strategic complements, Brécard (2012) conclude that if the green network effect is greater compared to the non-green network effect, the environmental quality of both products decreases. Conversely, if the non-green network effect dominates the green, environmental product quality seems to increase.

The second strand of literature directly focuses on the strategic interaction between product differentiation, the choice of R&D activities and product market competition. The impetus of the majority of these studies can be traced back to a comparison of welfare-implications based on a Bertrand and Cournot equilibrium, given the presence of (uncertain) product and/or process innovation's outcome[12]. We follow Dasgupta and Stiglitz (1980), d'Aspremont and Jacquemin (1988), Bester and Petrakis (1993), Suzumura (1992), Qiu (1997), Boone (2001) and others by, as mentioned above, solely focusing on process R&D activities. Further, we make the reasonable assumption that the innovation process is proportional to the investments in R&D. Hence, R&D activities are assumed to be deterministic.[13]

If we draw the two strands of literature together, we consequently arrive at a three-stage model which describes on the first stage the optimal process R&D choice directly affecting the cost structure of producing the green and/or the non-green product. Given the outcome of the first stage, on the second stage the competitors have to decide over the products' price levels, and given the outcome of the first and second stage, on the third stage, the firms have to decide on the environmental quality of the produced products.

By solving the game through backwards induction, we decompose an entrepreneur's incentive conducting process R&D by referring to the game's equilibrium conditions. In particular we show that an entrepreneur's incentive of conducting own process R&D, which in turn reduces production costs and hence increases welfare, is reduced due to the existence of knowledge-spillovers stemming from own R&D activities. Moreover we identify a strategic effect conducting R&D which reinforces the spillover-effect. We find that increasing R&D efficiency is welfare-increasing, whereas the existence of

[11]For a justification of the inclusion of network effects refer to Brécard (2012).

[12]For instance, refer to Motta (1993), Symeonidis (2003), Qiu (1997), and Vives (1985).

[13]Hence, our model directly corresponds to d'Aspremont and Jacquemin (1988), Suzumura (1992) and Qiu (1997). Contrary to Tishler and Milstein (2009), who discuss the relationship of uncertain R&D investments and firm survivability, we feel that this is a passable assumption as our focus is not to discuss market entry and exit incentives governed by uncertain outcomes of R&D investments.

knowledge-spillover tends to decrease welfare in the unregulated economy. Further, we find that due to imperfect competition, excessive product differentiation reduces environmental quality below the social optimal level. We show that a first-best solution can be realized by imposing, first, an *ad-valorem* tax, second, an emission-tax and, third, a process R&D subvention scheme. The article which combines environmental topics with industrial and public economics issues is part of the literature on the optimality of (environmental) taxation and on the literature of strategic effects of R&D activities.

3 The Setting

Central for our model is the assumption of a duopoly model of vertical product differentiation developed by Mussa and Rosen (1978), Cremer and Thisse (1994) and Cremer and Thisse (1999). A common feature of these models is that each firm produces under full information one vertically differentiated variant of a good and sets its price. Following Brécard (2012), we assume, first, that a green product exhibits a better quality than a standard product and, hence, is more expensive. Second, the remaining characteristics of the product are unaffected by changing the environmental items of the same product. Hence, the papers closest to the present one are Brécard (2012) and Lombardini-Riipinen (2005)[14]. However, this model presents two extensions that distinguish it from those papers significantly. First, it is assumed that each entrepreneur performs R&D investments to reduce its production costs and, second, as a direct consequence of R&D activities, knowledge spillovers as a positive externality in the production process have to be considered. The following subsections are devoted to the introduction of the key elements of the model. Subsection 3.4. explains the timing of the three-step game.[15]

3.1 Consumer Preferences

We assume a given continuum of consumers whose degree of environmental consciousness θ[16] is uniformly distributed over $[\underline{\theta}; \overline{\theta}]$ with unit density function $\underline{\theta} = \overline{\theta} - 1$ and

[14]As Brécard (2012) and Lombardini-Riipinen (2005) for instance, we assume free-market entry.

[15]It is worth noting that the setting is chosen in the way to guarantee an analytically tractable solution of the game.

[16]This interpretation of θ is in line with Lombardini-Riipinen (2005) and Moraga-Gonzáles and Padrón-Fumero (2002) for instance.

$\overline{\theta} > 1$. Each consumer has to decide whether to buy a green or brown quality q_i with $q_g > q_b$ and $i = \{b, g\}$. The subscript b stands for the lower brown quality, the index g represents the green product quality. Following Motta (1993), we assume that consumers' preferences are completely mapped by the following utility function:

$$U_i = \theta q_i - p_i, \tag{3.1}$$

where p_i stands for the price of product i[17]. Assuming full market coverage[18], we have to make sure that $\theta \geq \hat{\theta} \equiv \frac{p_b}{q_b}$. The representative consumer who is exactly indifferent to consuming one variant of the green or one variant of the brown product can be characterized by the environmental consciousness parameter $\breve{\theta}$ which can be computed as:

$$\breve{\theta} = \frac{p_g - p_b}{q_g - q_b}. \tag{3.2}$$

Using the information provided by equation (3.2), the demand for the high quality $n_g = \overline{\theta} - \breve{\theta}$ is given by: $n_g = \overline{\theta} + \frac{p_b - p_g}{q_g - q_b}$. Accordingly, the demand for the brown quality variant can be computed as: $n_b = 1 - \left(\overline{\theta} + \frac{p_b - p_g}{q_g - q_b}\right)$. To guarantee a market share $n_i \in (0, 1)$ for both firms i, we have to impose that $q_g > q_b$ and $(q_g - q_b)(\overline{\theta} - 1) < (p_g - p_b) < (q_g - q_b)\overline{\theta}$.

3.2 Environmental Quality

Following Brécard (2008), Brécard (2012) and Lombardini-Riipinen (2005), product environmental quality can be improved by increasing an entrepreneur's specific abatement effort defined by $(\overline{e} - e_i)$, with $\overline{e}$ as the per unit emission of firm i and e_i as the emission level per product unit after investing in an appropriate abatement technology. Hence, the total emission level $\Psi(e_i, n_i)$ of the economy directly reads as:

$$\Psi(e_i, n_i) = \Sigma_i[(\overline{e} - e_i)n_i]. \tag{3.3}$$

3.3 Production Sector

3.3.1 Production Costs

Each entrepreneur produces a good which is vertically differentiated in environmental quality. The ith entrepeneur's production technology assumed in this model implies

[17]Assuming a more general utility-function yields to a non-analytical solution of the game.

[18]For instance, we follow Brécard (2012) and Lombardini-Riipinen (2005) by assuming that the market is fully covered.

per unit variable cost, c_i which are assumed to be strictly increasing and convex in product environmental quality. In line with the relevant literature[19], we assume that an increase in the entrepreneur-specific abatement effort directly increases product quality and hence, leads to an immediate increase of each entrepreneur's variable production costs. Thus, the ith entrepreneur's variable per unit cost function reads as:

$$C_i(q_i) = \frac{1}{2} c q_i^2, \tag{3.4}$$

with $c > 0$ as a positively known constant[20].

3.3.2 Process R&D Activities

Additionally, each entrepreneur can reduce its variable unit production costs by conducting R&D investments. Conducting process R&D investments should shift the ith entrepreneur's marginal production costs downward[21]. Although there is little empirical evidence to which one can refer to model the functional of the R&D costs, most of the theoretically published literature suggest that R&D costs are linear or quadratic with respect to the specific R&D outcome. Among others, we refer to d'Aspremont and Jacquemin (1988), Qui (1997), Dasgupta and Stiglitz (1980) and Tishler and Milstein (2009) and assume that R&D costs are convex and strictly increasing in the respective R&D outcome $\chi_i > 0$ for $i = \{g, b\}$ and $i \neq j$. Hence, the R&D costs for the ith entrepreneurs's R&D program can be written as:

$$R_i(\chi_i) = \frac{1}{2} \chi_i^2 \text{ for } i = \{g, b\} \text{ and } i \neq j. \tag{3.5}$$

3.3.3 R&D Spillover

As primarily known from the endogenous growth theory, performing R&D investments opens the door for knowledge spillovers stemming from competitor's j R&D investments ($i \neq j$), which can be used for the purpose of reducing its own production costs even without performing own R&D. Hence, we follow the commonly made assumption that knowledge spillovers appear in the R&D outcomes[22]. Benefiting from this externality

[19]Refer to Cremer and Thisse (1999), Eriksson (2004), Conrad (2005), Lombardini-Riipinen (2005) and Brécard (2012).

[20]See Cremer and Thisse (1994) and Cremer and Thisse (1999).

[21]Of course, a R&D program can have demand enhancing and cost reduction effects simultaneously.

[22]Alternatively, spillovers can be directly associated with R&D investments. Refer to Amir (2000) for a comparison of these assumptions.

postulates that the rival entrepreneur is endued with sufficient absorptive capacities measured by the parameter $\xi \in (0,1)$. The larger ξ, the larger the absorptive capacities of the jth entrepreneur, and hence, the higher is the cost saving potential for his own production process. Alternatively, $\xi \in (0,1)$ can be interpreted as a measure of the tightness of an entrepreneur's knowledge network[23]. This interpretation is qualitatively in line with the contribution of Brécard (2012), who discusses the effects of green network effects on environmental product quality. While the contribution of Brécard (2012) focuses on the demand side of the model, the impetus here is the discussion of network effects on the production side.

3.4 Timing of the game

The design and the events of the game in the context of environmental quality and price-setting can be directly traced back to the contributions made by Lombardini-Riipinen (2005) and Brécard (2012). Obviously, the aforementioned contribution's game design consists of two-steps: In the first stage, firms compete in environmental product quality, whereas they compete in prices on the second stage. As we will see, modeling the choice of a process R&D program implies a three-step game. The timing of the game is as follows:

Stage 1: *Economy's entrepreneurs choose simultaneously their own process R&D activities. The outcome is given by* χ_i^* *with* $i \neq j$.

Stage 2: *Given the resulting R&D outcome* χ_i^* *with* $i \neq j$, *each entrepreneur decides on the environmental quality* q_i^*, $i \neq j$ *which will be offered to the consumers.*

Stage 3: *Given the results obtained from the first and second stage, both entrepreneurs decide on their offered prices* p_i^*, $i \neq j$.

4 Unregulated equilibrium

In this section, we present the solution of the game introduced in section 3.4. The game is solved with backward induction in order to obtain the sub-game perfect equilibria.

[23]The latter interpretation can be directly associated with the OECD's supported green growth strategy. Pursing green growth, one of the OECD's aims is to increase technology transfer which efficiency depends on knowledge-networks. For further details see OECD-WPSMEE (2010).

As mentioned above, we assume that $\bar{\theta}$ is chosen sufficiently high to ensure full market coverage[24].

Lemma 1. *$\forall\, \xi < \rho \in \left(0, \frac{3\sqrt{\frac{3}{2}}}{4c}\right)$, $\bar{\theta} \geq \frac{1}{4}\sqrt{7} + 1$ establish a pure-strategy and sub-game perfect equilibrium which is in line with full market coverage.*

Proof. See appendix A.7 □

4.1 Solution of Stage 3

The operating profit on stage 3 of each entrepreneur is given by

$$\pi_i^o(p_i, q_i, \chi_i, \chi_j) = [p_i - c_i(q_i) + \rho\chi_i + \xi\chi_j]n_i \text{ with } i \neq j. \tag{4.1}$$

As the entrepreneurs compete in prices on stage 3 of the game, p_i is chosen to maximize (4.1) given the price-setting behavior of its rival j. The outcome of the first sub-game results in the following prices:

$$p_g^* = \frac{1}{6}\left(2q_g\left(\bar{\theta} + cq_g + 1\right) - 2\bar{\theta}q_b + cq_l^2 - 2\left(\chi_g(\xi + 2\rho) + \chi_b(2\xi + \rho) + q_b\right)\right) \tag{4.2}$$

$$p_b^* = \frac{1}{6}\left(2\left(q_b\left(\bar{\theta} + cq_l - 2\right) - \chi_g(2\xi + \rho) - \chi_b(\xi + 2\rho)\right) - 2\left(\bar{\theta} - 2\right)q_g + cq_g^2\right). \tag{4.3}$$

Using the results given by equations (4.2) and (4.3), *ceteris paribus*, we can directly observe that increasing the entrepreneurs' R&D activities denoted by χ_i, $i \neq j$ obviously leads to a direct decrease of both product prices. We may conjecture that the price reduction of both offered qualities can be directly traced back to a strategic effect caused by conducting process R&D. Increasing its own R&D effort enables the ith entrepreneur to reduce its marginal costs, which in turn opens the door for *business stealing*[25] activities at the expense of its competitor j by decreasing p_i. Accordingly,

[24] Please refer to appendix A.7 which derives the conditions for full market coverage for the unregulated economy.

[25] To avoid confusion, the notion of the terminus *business stealing*, which can be primarily linked to Aghion and Howitt (1992) and others, is slightly different in our contribution. In the context of the endogenous growth theory, the terminus *business stealing* describes in its simplest fashion the fact that new technologies make old technologies obsolete. Firms therefore have an incentive to invest too much in R&D. In our model, we use the terminus to simply describe the fact that an entrepreneur can steal market shares from its competitor.

this forces entrepreneur j to reduce its prices as well, avoiding profit cuts. At the end of the day, the price reduction by j reduces the incentives for the ith entrepreneur conducting own process R&D. This result corresponds to the findings made by Lin and Saggi (2002).

Further, the negative strategic effect is reinforced by a negative spillover effect. Knowledge, which is generated from entrepreneurs' R&D activities, may spill over to competing entrepreneurs. The parameter ξ which appears in equations (4.2) and (4.3) measures the degree of knowledge spillovers. Now, it is rather obvious that increasing ξ reduces the rival's incentive of conducting own process R&D because everything equal, increasing ξ reduces the rival's product price level. In turn, knowing the rival's behavior, the existence of knowledge spillover will reduce the incentive to perform own process R&D as well.

Although we will discuss the interconnectedness of both effects more thoroughly in section 4.4, we can conjecture that increasing process innovation expenditures of both entrepreneurs induces a pronounced defensive price strategy for both competitors, which is reinforced by the strategic complementarities in prices.

4.2 Solution of Stage 2

Anticipating the product prices given by equations (4.2) and (4.3), each entrepreneur maximizes equation (4.1) to decide on the offered quality level q_i. In appendix A.1 we show that only one candidate for the quality game equilibrium satisfies both, the second-order conditions for an entrepreneur's operating profit maximization as well as the stability condition of the obtained equilibrium. This equilibrium is fully defined by the following quality vector

$$q_g^* = \frac{12\bar{\theta} + 8c(\xi - \rho)\left(\chi_g - \chi_b\right) + 3}{12c} \tag{4.4}$$

$$q_b^* = \frac{12\bar{\theta} + 8c(\xi - \rho)\left(\chi_g - \chi_b\right) - 15}{12c}. \tag{4.5}$$

Using equations (4.4) and (4.5), the demand for the green and brown products, n_g and n_b respectively, can be written as:

$$n_g^* = \frac{1}{18}\left[8c(\xi-\rho)\left(\chi_b-\chi_g\right)+9\right] \quad (4.6)$$

$$n_b^* = \frac{1}{18}\left[8c(\xi-\rho)\left(\chi_g-\chi_b\right)+9\right]. \quad (4.7)$$

Employing equations (4.2), (4.3), (4.4), (4.5), (4.6) and (4.7), the entrepreneurs' optimal operating profits of the second stage reads as:

$$\pi_g^{o*} = \frac{\left(8c(\xi-\rho)\left(\chi_b-\chi_g\right)+9\right)^2}{216c} \quad (4.8)$$

$$\pi_b^{o*} = \frac{\left(8c(\xi-\rho)\left(\chi_g-\chi_b\right)+9\right)^2}{216c}. \quad (4.9)$$

The existence of process R&D activities obviously generates two conflicting impacts on product's environmental quality induced by the strategic complementarities in product qualities[26].

On the one hand, all other things being equal, from equations (4.4) to (4.5) together with the assumption that $\rho > \xi$, we can directly deduce that increasing the process innovation activities for the green product χ_g, this negatively impacts the environmental qualities of both products by shifting the green entrepreneur's reaction function downwards and those of the brown entrepreneur to the upper left of the defined quality space. This reaction can be justified as follows: increasing χ_g lowers the marginal production costs of the green entrepreneur and, accordingly, enables the green entrepreneur to increase its own market share n_g and operating-profits at the expense of its competitor even by lowering its own product quality q_g[27]. Thus, for the case of the green entrepreneur it seems that the price-decreasing effect dominates the quality-reduction effect as n_g increases with decreasing $\breve{\theta}$. For the brown quality producing entrepreneur

[26] Let i denote the green entrepreneur. Inserting (4.2) and (4.3) in the operating-profits equation (4.1) and computing the cross partial derivative $\frac{\partial^2 \pi_i^o(\cdot)}{\partial q_i \partial q_j} = -\frac{1}{486}\left(-1.6\left(\chi_i-\chi_j\right)-9\right)\left(9-1.6\left(\chi_i-\chi_j\right)\right)$, we find that this expression is clearly positive for $\chi_i \in \left[\frac{9}{8c(\xi-\rho)}+\chi_j; \frac{9}{8c(\rho-\xi)}+\chi_j\right]$, together with $\rho > \xi$ and $i \neq j$. The same result can be obtained for the brown quality producing entrepreneur. Hence, the two qualities are strategic complementarities.

[27] The incentive to do so can be underpinned with the assumption made at the beginning of this paper that $q_g > q_b$ has to be fulfilled in any case.

however, the price-reduction effect, which tends to increase the demand for the brown quality does not offset the quality reduction effect which tends to decrease n_b and its operating profits. In this context it is worth noting that although reducing q_b obviously curbs the brown entrepreneur's operating profits, the brown entrepreneur has an incentive to do so, as cost-saving potentials induced by process R&D activities of the green entrepreneur tends to increase the brown entrepreneur's profit stream and hence, at least abates the negative effect on the brown entrepreneur's market share n_b and operating profit stream. This parallels the finding of Toshimitsu (2003).

On the other hand, increasing the process innovation activities of the brown product producing entrepreneur, χ_g, this positively affects both levels of offered product quality given $\rho > \xi$. Lowering its marginal costs, the brown quality q_b could be offered at a reduced price which enables the brown entrepreneur to steal market shares from the green entrepreneur. However, as the green entrepreneur still offers the higher quality, reducing the quality of q_b would directly curb the market share and operating profit stream of the brown quality producing entrepreneur. Instead, the brown quality producing entrepreneur has an incentive to increase its quality level as the green quality is a strategic complement for the brown entrepreneur. In turn, the green entrepreneur increases its produced product quality as well. In a nutshell, the price-decreasing effect which positively affects the brown entrepreneur's profit stream and market share is reinforced by an quality-increasing effect due to the strategic complementary of offered product qualities.

Moreover, the negative knowledge-spillover externality ξ directly influences prices, quantities, market share and the entrepreneur's operating profits differently. Given the green process R&D activities on stage two of the game are higher compared to those of the brown entrepreneur, which seems to be a reasonable assumption, this tends to increase both product qualities, given the knowledge-spillover externality ξ increases. This tends to decrease the market share n_g of the green entrepreneur from which in turn the brown entrepreneur benefits by increasing its market share and operating profit stream π_b^{o*}[28]. Although being negative for the green entrepreneur, the society's environmental quality seems to benefit from this source of knowledge-spillover exter-

[28]The green entrepreneur has an incentive to increase its product quality as the brown entrepreneur can decrease its product price more than the green entrepreneur, given ξ increases: $|\frac{\partial^2 p_g}{\partial \chi_g \partial \xi}| = \frac{1}{3} < \frac{2}{3} = |\frac{\partial^2 p_b}{\partial \chi g \partial \xi}|$. Doing so, the green entrepreneur is indeed not able to counterbalance the loss of market-share and operating-profit loss induced by the price reduction as ξ increases but increasing q_g works against the negative knowledge spillover effect as $\breve{\theta}$ decreases. Being strategic complementarities, the brown

nality. However, increasing the productivity of R&D process investments (ρ) tends to decrease the society's environmental quality by decreasing product quality, given $\chi_g > \chi_b$[29]. Given $\chi_g < \chi_b$, we obtain quite the opposite results[30]. Assuming $\chi_g = \chi_b$, the influence of ρ and ξ on prices, quantities, market share the entrepreneur's operating profits obviously vanishes due to the symmetric design of R&D activities.

As a direct consequence of the above outlined discussion, we can postulate the following proposition:

Proposition 1 *The equilibrium product differentiation has to be independent of process R&D investment activities conducted by the entrepreneurs. Moreover, product differentiation has to be independent of the knowledge-spillover externality ξ and the process R&D productivity ρ*[31].

Proof: Employing equations (4.4) and (4.9), equilibrium product differentiation reads as: $(q_g^* - q_b^*) = \frac{3}{2c}$ which depends solely on the positive constant c stemming from the entrepreneur's variable per unit cost function[32]. □

4.3 Solution of Stage 1

The objective of both entrepreneurs is to choose their optimal process R&D program such that their profits, defined as the operating profits given by the equations (4.8) and

quality rises as well.

[29]Now, the green entrepreneur has an incentive to decrease its product quality as the green entrepreneur can decrease its product price more than the brown entrepreneur, given ρ increases: $|\frac{\partial^2 p_g}{\partial \chi_g \partial \rho}| = \frac{2}{3} > \frac{1}{3} = |\frac{\partial^2 p_b}{\partial \chi g \partial \rho}|$. Still producing the higher quality but saving costs due to quality reduction, the green entrepreneur can increase its market-share and operating-profit at the expense of the brown-quality producing Entrepreneur as $\breve{\theta}$ decreases. Being strategic complementarities, the brown quality falls as well, which decreases production costs and *ceteris paribus* increases operating profits. Hence, this limits the negative consequences for the lower-quality producing Entrepreneur.

[30]The argumentation is similar to those given in footnotes 25 and 26, respectively. The arguments given in footnote 25 belong to the case where ρ increases, given $\chi_b > \chi_g$,whereas the arguments given in footnote 26 fit to the scenario where ξ increases, given $\chi_b > \chi_g$.

[31]These results offer similarities with the results found by Brécard (2012). She concludes that consumer network externalities do not impact product differentiation. A similar result is obtained by Lambertini and Orsini (2005). Although the origin of their examined externality (consumer vanity) is different from our (knowledge-spillover) and Brécard's (2012) (consumer conformity) study, finally, we arrive at the same implication valid for all afore mentioned studies: product differentiation is independent of the examined origin of externality.

[32]The result is identical to those obtained by Brécard (2012).

(4.9), respectively, net the R&D costs depicted by equation (3.5) will be maximized. Hence the profits are given by

$$\pi_g(\cdot) = \pi_g^{o*} - R_g = \frac{(8c(\xi - \rho)(\chi_b - \chi_g) + 9)^2}{216c} - \frac{\chi_g^2}{2} \quad (4.10)$$

$$\pi_b(\cdot) = \pi_b^{o*} - R_b = \frac{(8c(\xi - \rho)(\chi_g - \chi_b) + 9)^2}{216c} - \frac{\chi_b^2}{2}. \quad (4.11)$$

Maximization of equations (4.10) and (4.11) with respect to χ_g and χ_b, respectively, results in the Nash equilibrium in the entrepreneurs' R&D outcomes which are identical for both entrepreneurs and represented by:

$$\chi_i = \frac{2}{3}(\rho - \xi) \text{ for } i \neq j. \quad (4.12)$$

The second-order conditions require:

$$\frac{16}{27}c(\xi - \rho)^2 < 1 \text{ for } i \neq j. \quad (4.13)$$

The next proposition summarizes the conditions which have to be fulfilled simultaneously guaranteeing that the equilibrium with respect to the process R&D outcome – represented by equation (4.12) – is indeed a unique and stable interior solution[33].

Proposition 2 *The equilibrium defined by equation (4.12) is, first, a unique and, second, a stable interior non-deviation solution, given the following four conditions are simultaneously met:*

> Condition 1: *The second-order conditions for profit maximization represented by equation (4.13) are fulfilled.*

[33]The proposition is based on Tishler and Milstein (2009). However, Tishler and Milstein (2009) only provide conditions for an equilibrium being a unique and stable interior solution. But these conditions are only necessary for a Nash-equilibrium from which no player has an incentive to deviate from. Hence, we first prove that a given equilibrium offers a unique and stable interior solution and, given these assumptions are fulfilled, we proceed by investigating the non-deviation condition from that Nash-equilibrium. Details can be found in appendix A.2.

Condition 2: *The Routh-Hurwitz stability condition, which requires*

$$\left(\frac{\partial^2\pi_i(\cdot)}{\partial\chi_i^2}\frac{\partial^2\pi_j(\cdot)}{\partial\chi_j^2}\right) - \left(\frac{\partial^2\pi_i(\cdot)}{\partial\chi_i\partial\chi_j}\frac{\partial^2\pi_j(\cdot)}{\partial\chi_j\partial\chi_i}\right) > 0. \tag{4.14}$$

Condition 3: *The process R&D outcomes are strictly positive, that is,* $\chi_i > 0$ *for* $i \neq j$.

Condition 4: *The equilibrium represented by* (χ_g^*, χ_b^*) *has to fulfill the non-deviation conditions. These conditions are given as:*

$$\pi_g(\chi_g^*, \chi_b^*) \geq \pi_g(\chi_g, \chi_b^*),\ for\ \chi_g \geq 0 \tag{4.15}$$

$$\pi_b(\chi_g^*, \chi_b^*) \geq \pi_g(\chi_g^*, \chi_b),\ for\ \chi_b \geq 0. \tag{4.16}$$

Proof: See appendix A.2 and appendix A.3. □

As shown with appendix A.2 together with A.3, the equilibrium defined by equation (4.12) indeed defines a unique and stable interior solution from which no entrepreneur has an incentive to deviate from.

Figure 4.1 graphically represents the sub-game perfect process R&D equilibrium in the context of the stability conditions for the environmental quality game depicted in the R&D outcome space[34].
Hence, the identified parameter restriction $\chi_g \in \left[\frac{9}{8c(\xi-\rho)} + \chi_b; \frac{9}{8c(\rho-\xi)} + \chi_b\right]$, for $\rho > \xi$ and $i = \{g, b\}$ for $i \neq j$ guarantees an interior and stable solution, both, for the product's environmental quality, as well as for the process R&D game.

Now, we proceed by providing an interpretation of the obtained process R&D outcome Nash-equilibrium. Due to the symmetric specification of the knowledge-spillover influence (ξ) as well as of the productivity of the entrepreneur's own process R&D denoted by ρ, it is not surprising that the process R&D outcomes, represented by equation (4.12), are identical. Obviously, the optimal process R&D outcome for both entrepreneurs depends negatively on ξ and positively on ρ. This solution makes sense, as the incentive conducting own process R&D increases with the productivity of own

[34]With respect to figure 4.1, please note that $\left(\frac{\partial^2\pi_i(\cdot)}{\partial q_i^2}\frac{\partial^2\pi_j(\cdot)}{\partial q_j^2}\right) - \left(\frac{\partial^2\pi_i(\cdot)}{\partial q_i\partial q_j}\frac{\partial^2\pi_j(\cdot)}{\partial q_j\partial\chi_i}\right) = -\frac{c^2(8c(\xi-\rho)(\chi_g-\chi_b)-9)(8c(\xi-\rho)(\chi_g-\chi_b)+9)}{1458} \equiv \Xi > 0$ for $\chi_g \in \left(\frac{9}{8c(\xi-\rho)} + \chi_b; \frac{9}{8c(\rho-\xi)} + \chi_b\right)$. Please refer to appendix A.1.

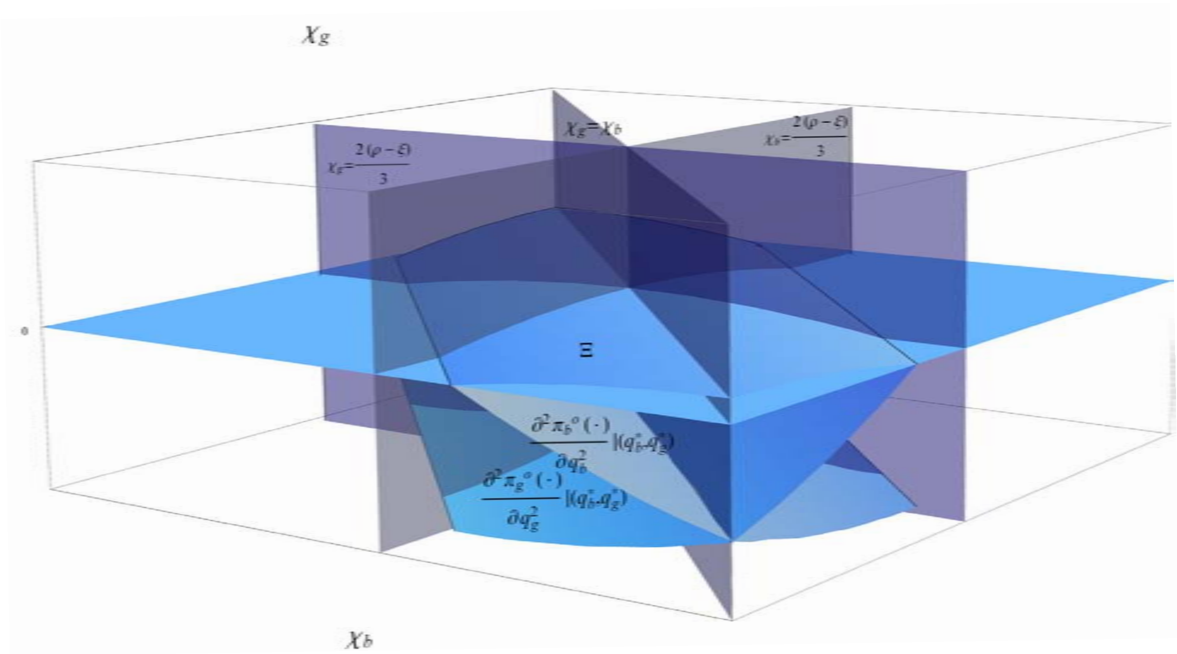

Figure 4.1: Graphical representation of the sub-game perfect process R&D equilibrium

process R&D endeavors but is attenuated by the chance of benefiting from knowledge-spillover from rivals' R&D efforts. Hence, this findings extends the results of Lin and Saggi (2002) as not only the rival's price reduction reduces the incentives conducting own process R&D but also the possibility benefiting from knowledge-spillover. We may conjecture that the strategic price effect and the knowledge-spillover effect reinforce each other.

Given the solution of the R&D outcomes denoted by equations (4.12), we can directly infer from that optimality condition on the prices, the demand for the green and brown product, as well as the entrepreneur's profits. Using equations (4.2), (4.3), (4.4) and (4.5) with (4.12), the prices are given as:

$$p_g^{**} = \frac{1}{96}\left[24\bar{\theta}\left(2\bar{\theta}+1\right)+64(\xi^2-\rho^2)+75\right] \tag{4.17}$$

$$p_b^{**} = \frac{1}{96}\left[24\bar{\theta}\left(2\bar{\theta}-5\right)+64(\xi^2-\rho^2)+147\right]. \tag{4.18}$$

Obviously, product prices tend to decrease non-linearly by increasing ρ and increase non-linearly by increasing ξ. Once again, this reflects, on the one hand, the cost-reduction effect of conducting own process R&D (ρ) and, on the other hand, it impressively shows that the existence of knowledge spillover (ξ) tends to increase the price level as product quality is increasing to compensate the loss of market share and operating profit cuts caused by the rival's process R&D price level reduction. Hence, these results confirm our conjectures regarding the strategic complements of product prices as well as environmental product qualities[35].

It is straightforward that product differentiation is still given by $(q_g^{**} - q_b^{**}) = \frac{3}{2c}$. Employing equations (4.6) and (4.7) together with (4.12), the demand for green and brown product qualities is $n_i = 0.5$ for $i = \{g, b\}$ as equilibrium R&D outcomes are identical. Hence, Entrepreneur's operating profits based on equations (4.8) and (4.9) are the same and can be calculated as $\pi_i^* = \frac{3}{8c}$ for $i = \{g, b\}$. The equilibrium environmental consciousness parameter $\breve{\theta}$ at which a representative consumer is indifferent between demanding a green or brown product quality, is the same as computed by Lombardini-Riipinen (2005) and given as

$$\breve{\theta} = \bar{\theta} - \frac{1}{2}. \tag{4.19}$$

Hence, endogenizing process R&D investments on stage 3 reduces

$$\breve{\theta} = \frac{1}{18}\left(18\bar{\theta} + 8c(\xi - \rho)\left(\chi_g - \chi_b\right) - 9\right) \tag{4.20}$$

to equation to (4.19)[36].

4.4 Decomposition of process R&D incentives

In sections 4.1 and 4.2 we have made some conjectures regarding strategic behavior of both entrepreneurs regarding process R&D investments. For instance, we have stated that both entrepreneurs have an incentive to under-invest in process R&D due to the

[35] Please note that this result is not at odds with the discussion regarding the quality- and price-setting behavior of the entrepreneurs accomplished in sections 4.1. and 4.2. For instance, the prices represented by equations (4.17) and (4.18) results, given both entrepreneurs optimally choose their level of environmental product-quality and process R&D outcome.

[36] If we reduce the three-step game to a two-step game by neglecting the R&D choice, we finally arrive at equation (4.20). Obviously, the spillover parameter ξ affects the environmental consciousness parameter $\breve{\theta}$ in a positive or negative manner, depending on the sign of $\chi_g - \chi_b$. Although in our model, the spillover-effect appears on the supply side and not as in Brécard's (2012) set-up, on the demand side of the model, qualitatively we arrive at the same result, that is, the spillover effect directly affects the consumer's taste parameter regarding environmental consciousness. In this way the model in this paper can be seen as a qualitative generalization of the models proposed by Brécard (2012) and Lombardini-Riipinen (2005).

existence of knowledge-spillovers. In this section we present the key to understand this result, that is to carefully decompose the relevant factors that particularly induce an entrepreneur to undertake process R&D investments. We follow Qiu (1997) and decompose the consequences of process R&D investments in four parts. Using an entrepreneur's profit definition based on equation (4.10) or (4.11), after some algebraic manipulations evaluated at the equilibrium on the first stage of the game[37], for the i-th entrepreneur, $i \neq j$, we arrive at

$$\begin{aligned} \frac{\partial \pi_i(\cdot)}{\partial \chi_i} &= \frac{\partial \pi_i(\cdot)^o}{\partial q_j}\frac{\partial q_j}{\partial \chi_i} + \frac{\partial \pi_i(\cdot)^o}{\partial \chi_i} - \frac{\partial R_i(\cdot)}{\partial \chi_i} \\ &= \underbrace{\left(\frac{1}{\Xi}\right)}_{>0}\underbrace{\left(\frac{2c(\rho-\xi)}{9}\right)}_{>0 \text{ as } \rho>\xi}\vartheta\left\{\underbrace{\left(\frac{\partial^2 \pi_j(\cdot)}{\partial q_i \partial q_j}\frac{\partial \pi_i(\cdot)}{\partial q_j}\right)}_{ste<0} + \underbrace{\left(-\frac{\partial^2 \pi_i(\cdot)}{\partial q_i^2}\frac{\partial(\cdot)\pi_i}{\partial q_j}\right)}_{spe<0}\right\} + \underbrace{\frac{\partial \pi_i(\cdot)^o}{\partial \chi_i}}_{sie>0} - \underbrace{\frac{\partial R_i(\cdot)}{\partial \chi_i}}_{coe<0}, \end{aligned} \tag{4.21}$$

with $i = \{g, b\}$ and $i \neq j$. $\vartheta = 1\boldsymbol{I}_{[i=h]} - 1\boldsymbol{I}_{[i=b]}$, with $\boldsymbol{I}_{[\cdot]}$ represents an indicator function. Moreover, with respect to proposition 2, we have shown that $\left(\frac{\partial^2 \pi_i(\cdot)}{\partial q_i^2}\frac{\partial^2 \pi_j(\cdot)}{\partial q_j^2}\right) - \left(\frac{\partial^2 \pi_i(\cdot)}{\partial q_i \partial q_j}\frac{\partial^2 \pi_j(\cdot)}{\partial q_j \partial q_i}\right) = -\frac{c^2(8c(\xi-\rho)(\chi_g-\chi_b)-9)(8c(\xi-\rho)(\chi_g-\chi_b)+9)}{1458} \equiv \Xi > 0$. From equation (4.21) we can directly infer that first, increasing an entrepreneur's process R&D activity directly reduces the production cost, and hence, for a given cost reduction potential, directly increases the entrepreneur's operating profits. Thus, the size effect of process R&D, *sie*, is always positive[38]. Second, increasing own process R&D directly increases the rival's cost. Obviously, this is detrimental for conducting own process R&D endeavors. Hence, the spillover effect, *spe*, is negative. Third, decreasing own production costs directly affects the rival's price and environmental quality output decision: Increasing χ_i encourages the j-th rival to be tougher in the market and hence increases his profits at the expense of the process R&D conducting entrepreneur. This again reflects the strategic complementarities in product prices as well as in product environmental quality, and as a direct consequence, the strategic effect, *ste* turns out to be negative. Finally, R&D activities are costly, which implies that the cost effect *coe* is clearly negative. In a nutshell, by decomposing R&D incentives, we finally confirm our conjectures accomplished in section 4.1 and 4.2. We now turn to the welfare-implications of the unregulated economy.

[37] Refer to appendix A.5 for the derivation of expression (4.21).

[38] Please note that the size effect for both entrepreneurs is strictly positive as $\chi_g \in \left(\frac{9}{8c(\xi-\rho)} + \chi_b; \frac{9}{8c(\rho-\xi)} + \chi_b\right)$ with $\rho > \xi$.

4.5 Welfare

Given products have been sold at prices given by equations (4.2) and (4.3), with equilibrium quantities denoted by equations (4.4) and (4.5), and both evaluated at optimal R&D outcomes represented by (4.12), the unregulated economy's welfare $\mathcal{W}^u$ is defined as

$$\mathcal{W}^u \equiv \int_{\bar{\theta}-1}^{\breve{\theta}} [U_b(\theta)df(\theta)] + \int_{\breve{\theta}}^{\bar{\theta}} [U_g(\theta)df(\theta)] + \sum_i \pi_i - \Theta(E), \tag{4.22}$$

with $\Theta \equiv \delta\Psi$ and $\Psi \equiv \Sigma_i[(\bar{e} - e_i)x_i]$ as the total emission level defined in equation (3.3). δ is a positive parameter which weights the importance of environmental quality for the society.

Equation (4.22) can be further re-expressed as:

$$\mathcal{W}^u = \frac{1}{96}\left[48\bar{\theta}\left(\bar{\theta} + 2\delta - 1\right) - 96\delta\bar{e} - 48\delta + 64\left(\rho^2 - \xi^2\right) + 3\right]. \tag{4.23}$$

Proposition 3 *From equation (4.23) we can directly infer that society's welfare increases by increasing the efficiency of process R&D activities ρ, whereas increasing knowledge-spillover effects (ξ) decreases welfare. Given $\rho = \xi$, welfare remains unaffected by varying ξ or ρ. Further, a higher emission level $\bar{e}$ decreases welfare by $\delta > 0$.*
Proof: Referring to equation (4.23), taking partial derivatives of $\mathcal{W}^u$ with respect to ρ, ξ and $\bar{e}$, we finally arrive at: $\frac{\partial \mathcal{W}^u}{\partial \rho} = \frac{4\rho}{3} > 0$, $\frac{\partial \mathcal{W}^u}{\partial \xi} = -\frac{4\xi}{3} < 0$ and $\frac{\partial \mathcal{W}^u}{\partial \bar{e}} = -\delta < 0$. □

5 The first-best optimum

In this section, our aim is to determine the social optimal policy in the presence of process R&D investments. To achive this goal, we follow Cremer and Thisse (1999), Lombardini-Riipinen (2005), Brécard (2012), and derive the first-best optimum of an economy. A first-best optimum of an economy is realized, if, first, the social marginal cost of production equals the marginal benefit of consumption. Additionally, the society's consumers have to be optimally allocated between the offered qualities. This requires that the environmental consciousness parameter θ is chosen socially optimal, that is, it represents the marginal consumer who is exactly indifferent to purchasing the green or brown environmental quality product, both offered at marginal costs.

The optimal prices in the social planner's economy reflect the marginal costs of production, the marginal environmental damage as well as the costs conducting process R&D activities net the marginal benefits of process R&D activities. Accordingly, the optimal prices are then given by[39]:

$$
\begin{aligned}
p_g^o &= 0.5q_l^2 + \frac{\chi_b^2}{2} + \delta\left(\bar{e} - q_l\right) - \xi\chi_g - \rho\chi_b && (5.1)\\
p_b^o &= 0.5q_h^2 + \frac{\chi_g^2}{2} + \delta\left(\bar{e} - q_h\right) - \rho\chi_g - \xi\chi_b. && (5.2)
\end{aligned}
$$

Further, the optimal environmental consciousness parameter at which the representative consumer is indifferent consuming a green or brown quality product $\breve{\theta}^o$ reads as

$$\breve{\theta}^o = \frac{p_g^o - p_b^o}{q_g - q_b}. \tag{5.3}$$

The social optimal product differentiation level $(q_g^o - q_b^o)$, as well as the levels of optimal process R&D outcomes χ_b^o and χ_g^o can be obtained by solving the social planer's problem:

$$max_{q_b^o,q_g^o,\chi_b^o,\chi_g^o}\left\{\int_{\bar{\theta}-1}^{\breve{\theta}^o}[\theta q_b^o - p_b^o)d\theta] + \int_{\breve{\theta}^o}^{\bar{\theta}}[\theta q_g^o - p_g^o)d\theta]\right\}. \tag{5.4}$$

Employing equations (5.1), (5.2) and (5.3) together with (5.4), the social optimal environmental product qualities read as:

$$
\begin{aligned}
q_g^{o*} &= \frac{1}{4}\left(4\bar{\theta} + 4\delta + 4\left(\chi_g - \chi_b\right)\left(\chi_g + \chi_b + 2\xi - 2\rho\right) - 1\right) && (5.5)\\
q_b^{o*} &= \frac{1}{4}\left(4\bar{\theta} + 4\delta + 4\left(\chi_g - \chi_b\right)\left(\chi_g + \chi_b + 2\xi - 2\rho\right) - 3\right). && (5.6)
\end{aligned}
$$

[39]Please note that the superscript o in this section stands for optimal.

Based on (5.4), taking the first-order derivatives with respect to χ_b^o and χ_g^o, the optimal levels of the process R&D outcome are identical for both entrepreneurs and read as:

$$\chi_i^{o*} = \rho + \xi, \text{ for } i \neq j. \tag{5.7}$$

Employing equations (5.5), (5.6) and (5.7), we directly observe the *ex-ante* expected result that the social optimal product differentiation level $(q_g^o - q_b^o) = \frac{1}{2c}$ is lower compared to the unregulated solution $((q_g^* - q_b^*) = \frac{3}{2c})$ derived before. For the social-optimal environmental consciousness parameter we calculate $\breve{\theta}^o = -0.5 + \bar{\theta}$ which obviously equals $\breve{\theta}$ represented by equation (4.19). The latter finding motivates the following result.

Result 1 *The unregulated equilibrium guarantees the optimal allocation of consumers across the environmental quality space.*

Based on equation (5.7) we can directly deduce the following insightful result:

Result 2 *The social optimal process R&D outcomes are higher compared to those for the unregulated economy as* $(\chi_i^{o*} - \chi_i^*) = \frac{1}{3}(5\xi + \rho) > 0$, *for* $i \neq j$.

This second result can be entirely understood in terms of the internalization of the knowledge-spillover effect. The social planer obviously internalizes this effect, whereas the decentralized and unregulated solution does not. Hence, the decentralized and unregulated solution shows a myopic behavior of the economy's entrepreneurs: As argued above, the existence of the spillover-effect which is reinforced by the negative strategic-effect generates the incentive for underinvestment in process R&D.

Employing equation (5.4) together with equations (5.1), (5.2), (5.5), (5.6) and (5.7) the social optimal welfare can be therefore calculated as:

$$\mathcal{W}^o = \frac{-32c\delta\bar{e} + 16\bar{\theta}\left(\bar{\theta} + 2\delta - 1\right) + 16c(\xi + \rho)^2 + 16(\delta - 1)\delta + 5}{32c}. \tag{5.8}$$

We therefore establish the following proposition:

Result 3 *The first-best optimal welfare is higher compared to the welfare at the unregulated equilibrium.*

This can be traced back to two reasons: First, in contrast to the unregulated equilibrium, the first-best optimum takes the knowledge-spillovers appropriately into account, and, thus increases welfare as can be directly seen from consulting equation (5.4). Second, as mentioned by Brécard (2012), the overall socially optimal pollution level Θ^o is lower compared to the unregulated equilibrium: $(\Theta - \Theta^o) = \left(\frac{2c\bar{e}-2\bar{\theta}+1}{2c}\right) - \left(\frac{2c\bar{e}-2\bar{\theta}-2\delta+1}{2c}\right) = \frac{\delta}{c} > 0$.

6 Optimal taxation and second-best solution

We now proceed by discussing the regulated economy. Referring to Result 1, we know that the unregulated equilibrium deduced in section 4 of this contribution guarantees an optimal allocation of consumers across the quality space. As a direct consequence of that we only need three fiscal instruments inducing a first-best solution. The set of fiscal instruments is designed to, (i) correct for the entrepreneur's market power, (ii) to correct for the negative pollution externality, and, (iii) to correct for the knowledge-spillover externality induced by process R&D investments.

We draw on the framework proposed by Lambertini and Orsini (2005), Lombardini-Riipinen (2005) and Brécard (2012) and introduce, first, a product tax $\tilde{\tau}_v$ designed as an *ad-valorem* tax which, as we will observe, directly decreases product differentiation. Second, as product quality tends to decrease by the product tax, we envisage further an emission tax $\tau_e \in [0, \infty^+)$. Third, we introduce a subsidy scheme with a corresponding subsidy rate $\tau_s \in (0, 1)$ to foster the incentive to increase an entrepreneur's own process R&D. Hence, the subsidy scheme works against the incentive to reduce own process R&D caused by the knowledge-spillover externality.

As the demand side is obviously not affected by the envisaged set of fiscal policies, based on equation (4.1), we proceed by introducing the adjusted operating profits of both entrepreneurs. With the set of fiscal policies, they now read as[40]:

$$\pi_i^{or}(p_i, q_i, \chi_i, \chi_j) =$$

[40] The superscript r stands for regulated and o for operating.

$$[1-\tilde{\tau}_v]\left[p_i - \frac{c_i(q_i)}{1-\tilde{\tau}_v} + \left(\frac{\rho}{1-\tilde{\tau}_v}\right)\chi_i + \left(\frac{\xi}{1-\tilde{\tau}_v}\right)\chi_j - \left(\frac{\tau_e}{1-\tilde{\tau}_v}\right)(\bar{e}-q_i)\right] n_i, \qquad (6.1)$$

with $i \neq j$ and $\tau_v \equiv \left(\frac{1}{1-\tilde{\tau}_v}\right)$ defined over $\tau_v \in [1, \infty^+[$ as a corresponding *ad-valorem* index suggested by Cremer and Thisse (1994). Of course, the subsidy rate does not affect entrepreneur's operating-profits and hence operating profit maximization.

Now, we follow the same steps as proposed in section 4 to solve the three-stage game. To conserve space, we focus on the sub-game perfect equilibria on the second and first stage. Based on the profit functions given by equation (6.1), we show in appendix A.6 that only one set of quality pairs fulfill the second-order conditions and, moreover, ensure positive profits. This pair of qualities, which ensures a stable, interior solution is given by

$$q_g^{*r} = \frac{12\bar{\theta} + 8c(\xi-\rho)\tau_v^2(\chi_g - \chi_b) + 12\tau_e\tau_v + 3}{12c\tau_v} \qquad (6.2)$$

$$q_b^{*r} = \frac{12\bar{\theta} + 8c(\xi-\rho)\tau_v^2(\chi_g - \chi_b) + 12\tau_e\tau_v - 15}{12c\tau_v}. \qquad (6.3)$$

From equations (6.2) and (6.3) we directly observe a trade-off between a higher environmental product quality and a reduction of product differentiation: product quality is increased by the imposed environmental tax while the *ad-valorem* tax alone tends to decrease economy's environmental quality by decreasing product differentiation: $(q_g^{*r} - q_b^{*r}) = \frac{3}{2c\tau_v}$. This result is in line with Cremer and Thisse (1994) and identical to those derived by Brécard (2012) and Lombardini-Riipinen (2005).

Accordingly, the demand for the green and brown products, n_g^r and n_b^r respectively, can be derived as:

$$n_g^{*r} = \frac{1}{18}\left(9 - 8c(\xi-\rho)\tau_v^2(\chi_g - \chi_b)\right) \qquad (6.4)$$

$$n_b^{*r} = \frac{1}{18}\left(9 + 8c(\xi-\rho)\tau_v^2(\chi_g - \chi_b)\right). \qquad (6.5)$$

It is rather obvious that increasing the *ad-valorem* tax tends to stimulate the demand of the green quality at the expense of the brown quality, given the R&D outcome of the high-quality producing entrepreneur exceeds the R&D efforts of its competitor, $\chi_g > \chi_b$ and given $\rho > \xi$ holds per assumption. Given $\chi_g = \chi_b$ the market is equally shared between both entrepreneurs: $n_g^* = n_b^* = 0.5$.

Referring to equations (6.2), (6.3), (6.4) and (6.5), the entrepreneurs' operating profits on the second stage changes to:

$$\pi_g^{or*} = \frac{(9 - 8c(\xi - \rho)\tau_v^2 (\chi_g - \chi_b))^2}{216c\tau_v^2} = \frac{18}{216c\tau_v^2}(n_g^{*r})^2 \tag{6.6}$$

$$\pi_b^{or*} = \frac{(9 + 8c(\xi - \rho)\tau_v^2 (\chi_g - \chi_b))^2}{216c\tau_v^2} = \frac{18}{216c\tau_v^2}(1 - n_g^{*r})^2. \tag{6.7}$$

Given $\chi_g \neq \chi_b$, the regulated operating-profits of both entrepreneurs solely depends on the *ad-valorem* tax τ_v: Increasing τ_v directly decreases the high-quality operating profits in favour of the low-quality operating profits, given $\chi_g < \chi_b$, and vice versa[41]. Additionally, from equations (6.6) and (6.7) we directly observe that the operating-profits are not affected by the regulator's imposed emission tax τ_e.

The solution of the first stage of the game delivers the optimal process R&D outcome for the regulated economy. As we have concluded in section 5 by establishing the second result, the optimal level of process R&D outcome resulting for the unregulated economy is too low compared to the social optimal solution. Hence, we impose that the regulator has to subsidize the level of process R&D activities with a subsidy rate $\tau_s \in (0, 1)$. Hence, the optimization problem defined by the equations (4.8) and (4.9) net the R&D costs given by equation (3.5) has to be adjusted accordingly. The profits change to:

$$\pi_g^r = \frac{(9 - 8c(\xi - \rho)\tau_v^2 (\chi_g - \chi_b))^2}{216c\tau_v^2} - \frac{1}{2}\chi_g^2 (1 - \tau_s) \tag{6.8}$$

$$\pi_b^r = \frac{(9 + 8c(\xi - \rho)\tau_v^2 (\chi_g - \chi_b))^2}{216c\tau_v^2} - \frac{1}{2}\chi_b^2 (1 - \tau_s). \tag{6.9}$$

Maximization of equations (6.8) and (6.9) with respect to χ_g and χ_b results in the Nash-equilibrium regarding the regulated entrepreneurs' R&D outcomes which are given by:

[41]This can be seen as follows: $\frac{\partial \pi_g^{or*}}{\partial \tau_v} = \frac{\partial \pi_g^{or*}}{\partial n_g^{*r}} \frac{\partial n_g^{r*}}{\partial \tau_v}$, which is negative, given $\frac{\partial n_g^{r*}}{\partial \tau_v} < 0$. To be true, the latter requires $\chi_g < \chi_b$ with $\rho > \xi$.

$$\chi_i^{*r} = \frac{2(\rho - \xi)}{3\,(1 - \tau_s)} \text{ for } i \neq j. \tag{6.10}$$

It is straightforward to observe from equation (6.10) that *ceteris paribus* the regulated R&D outcome is increasing in the subsidy-rate τ_s for both products and is higher compared to the unregulated solution represented with equation (4.12), given $\tau_s \in (0, 1)$.

The second-order conditions which are more restrictive due to the existence of the subsidy-rate τ_s compared to the unregulated equilibrium now require:

$$\frac{16}{27} c(\xi - \rho)^2 + \tau_s < 1 \text{ for } i \neq j. \tag{6.11}$$

Proposition 4 *The regulated economy's process equilibrium process R&D outcome which is represented by equation (6.10) is a unique and stable interior solution.*

Proof. See appendix A.5 □

As stated above, the *simultaneous* implementation of the fiscal policy menu consisting of the *ad-valorem* tax τ_v, the emission tax τ_e and the subsidy-rate τ_s will induce the first-best solution derived in section 2. Technically spoken, we have to solve a three-dimensional system of equations consisting of both entrepreneurs' R&D outcomes and environmental quality-levels[42]. The unique solution to this problem is presented in the next proposition.

Proposition 5 *The implementation of the fiscal menu $(\tau_s^o, \tau_e^o, \tau_v^o)$ induces a first-best optimum, given the absence of administrative costs. The menu as the single solution of a three-dimensional system of equations $q_i^o = q_i^{*r}$ and $\xi_i^o = \xi_i^{*r}$ for $i = \{g, b\}$ and $i \neq j$ can be characterized as follows:*

$$(\tau_s^o, \tau_e^o, \tau_v^o) = \left(\frac{5\xi + \rho}{3(\xi + \rho)}, \frac{2\bar{\theta}}{3} + \delta - \frac{1}{3}, 3 \right). \tag{6.12}$$

[42]As the sub-game equilibrium R&D outcome is the same for both entrepreneurs, the system reduces from dimension four to three.

Referring to the relevant literature we find that both, the optimal *ad-valorem* tax index $\tau_v = 3$ or the optimal *ad-valorem* tax $\tilde{\tau}_v = \frac{2}{3}$, as well as the optimal environmental tax $\tau_e = \delta + \frac{2}{3}\left(\bar{\theta} - \frac{1}{2}\right)$ is the same as those derived by Lombardini-Riipinen (2005) and Brécard (2012). However, this result is not remarkable as the parameters ρ and ξ which are directly linked to each entrepreneur's process R&D activities do not affect either the entrepreneur's product differentiation nor the level of emissions. Thus, apart from the first stage of the game, the model presented in this contribution can be viewed as isomorph to those models presented by Lombardini-Riipinen (2005) and Brécard (2012).

The optimal process R&D subsidy rate τ_s^o obviously decreases with the R&D productivity parameter ρ and increases with the knowledge-spillover parameter ξ. Hence, the process R&D subsidy policy tends to reduce the incentives for under-investment in process R&D induced by the spillover effect and reinforced by strategic effect derived in section 4.4.

In contrast to the welfare definition for the unregulated economy denoted by $\mathcal{W}^u$ in equation (4.22), for the case of the regulated economy discussed in this section, we have to acknowledge the governmental fiscal budget $\Psi(E, \chi_i, \chi_j)$ which is defined as the revenues coming from the emission tax based on the regulated emission level E^{*r} net the expenditures for the entrepreneur's process R&D subsidies. Hence, the regulated welfare $\mathcal{W}^r$ has to be defined as

$$\mathcal{W}^r \equiv \int_{\bar{\theta}-1}^{\breve{\theta}} [U_b(\theta) df(\theta)] + \int_{\breve{\theta}}^{\bar{\theta}} [U_g(\theta) df(\theta)] + \sum_i \pi_i - \Theta(E) + \Psi(E, \chi_i, \chi_j), \tag{6.13}$$

with $\Psi(E, \xi_i, \xi_j) \equiv \tau_e E^{*r} - \sum_i \tau_s \frac{\chi_i^2}{2}$ for $i \neq j$.

Using the optimal levels of process R&D outcome represented by equation (6.10), the optimal prices[43] and quantities given by equations (6.2) and (6.3), respectively, and the optimal level of demanded green and brown product qualities represented by equations (6.4) and (6.5), respectively, the regulated welfare $\mathcal{W}^r$ can be re-expressed as:

$$\mathcal{W}^r = \frac{-16\tau_v^2\left(2c\bar{e}\left(\delta - \tau_e\right) + \tau_e\left(-2\bar{\theta} - 2\delta + 2\tau_e + 1\right) + \frac{8c(\xi-\rho)^2\tau_s}{9(\tau_s-1)^2}\right)}{32c\tau_v^2} +$$

[43] The optimal prices for the regulated economy are read as $p_g^r = \frac{9\left(16\tau_v^2\left(2c\bar{e}\tau_e - c\chi_g(\xi+\rho) - \tau_e^2\right) + 25\right) + 8\left(3\bar{\theta}\left(8c(\xi-\rho)\tau_v^2(\chi_g - \chi_b) + 3\right) + 18\bar{\theta}^2 + 2c\tau_v^2\left(4c(\xi-\rho)^2\tau_v^2(\chi_g-\chi_b)^2 - 9\chi_b(\xi+\rho)\right)\right)}{288c\tau_v}$ and $p_b^r = \frac{48\tau_v^2\left(6c\bar{e}\tau_e + c\chi_g(\rho - 7\xi) - 3\tau_e^2\right) + 8\left(3\bar{\theta}\left(8c(\xi-\rho)\tau_v^2(\chi_g-\chi_b) - 15\right) + 18\bar{\theta}^2 + 2c\tau_v^2\left(4c(\xi-\rho)^2\tau_v^2(\chi_g-\chi_b)^2 + 3\chi_b(\xi - 7\rho)\right)\right) + 441}{288c\tau_v}$.

$$+\frac{16\tau_v^3\left(-2c\bar{e}\tau_e+\frac{4c(\xi-\rho)(\xi+\rho)}{3(\tau_s-1)}+\tau_e^2\right)+\tau_v\left(16\bar{\theta}\left(\bar{\theta}+2\delta-2\tau_e-1\right)-16\delta+16\tau_e-23\right)+24}{32c\tau_v^2}. \tag{6.14}$$

Theoretically, the agency can dispose of the entire toolbox of fiscal instruments. However, as pointed out by Baumol and Oates (1988), in reality, the environmental agency is often restricted to use only a sub-set of the fiscal menu. Further, as some strands of the political economy literature suggest, due to lobbying, the acceptance of a certain policy directive may hinder the initialization of a first-best optimum[44]. This brings us to think about the initialization of a second-best solution, which we should compare with the unregulated solution instead of comparing the first-best solution given by equation (6.14) with the unregulated solution.

7 Second-best welfare

This section deals with the discussion of an implementation of a second-best solution by the environmental agency. Given we ignore the *ad-valorem*-tax, which tends to increase the economy-wide emission level given by $E^r = \frac{2\tau_v(c\bar{e}-\tau_e)-2\bar{\theta}+1}{2c\tau_v}$[45], and hence, should not be seen as a suitable instrument[46] to tackle environmental problems and working towards sustainability. Contrary to the *ad-valorem* tax, the process R&D subsidy policy obviously does not directly affect the environmental emission level, but affects environmental product quality and potentially could increase welfare[47]. Thus, for the environmental agency, we may conjecture that it seems *ex-ante* attractive to use both instruments to implement an appropriate environmental fiscal policy scheme. Consequently, the question arises what the regulator's second-best policy is, assuming the authority is empowered to set only the environmental tax and/or the process R&D

[44] Refer to Aidt (1998) for instance.

[45] This can be seen as follows: The first-order derivative of $E(\cdot)^r$ with respect to τ_v is positive for sufficiently large $\bar{\theta}$: $\frac{\partial E(\cdot)}{\partial \tau_v} = \frac{2\bar{\theta}-1}{2c\tau_v^2}$. Assuming full market coverage, the derivative is clearly positive as appendix A.8 shows that full market coverage is guaranteed, given $\bar{\theta} \geq \frac{1}{4}\sqrt{\frac{640\tau_v^2(3\bar{e}\tau_e(\tau_s-1)-2(\xi-\rho)(\xi+\rho))}{3(\tau_s-1)}+25}-\tau_e\tau_v+1$.

[46] See Brécard (2008), Brécard (2012) and Lambertini and Orsini (2005).

[47] Based on equation (6.14), we observe that welfare is increasing, given $\tau_s < 1+\frac{4(\xi-\rho)}{2(\rho-\xi)+3(\xi+\rho)\tau_v}$ for $\rho > \xi$.

subsidy-rate. The following subsections are directly devoted to a discussion regarding the welfare implications by employing different combinations of fiscal instruments available from the regulator's toolbox.

7.1 Second-best welfare with pollution tax τ_e

If the regulator is only empowered to set the environmental pollution tax τ_e, welfare defined by equation (6.14) changes to:

$$\mathcal{W}^{r1} = \mathcal{W}^{u} + \frac{\tau_e\,(2\delta - \tau_e)}{2c}. \tag{7.1}$$

The solution to the regulator's game, maximizing welfare given by equation (7.1), is to set δ, which is the society's valuation of pollution level, equal to the emission tax τ_e. As $\Theta \equiv \delta\Psi$, δ can be alternatively interpreted as the marginal environmental damage. This motivates the following result.

Result 4 *Given the absence of administrative costs, welfare* $\mathcal{W}^{r1}$ *is increasing, given* $\tau_e < \delta$*. Further, the second-best emission-tax* $\tilde{\tau}_e$ *equals the Pigouvian tax rate* δ *as the single solution of the regulator's game.*

Prima facie, the results seem to be at odds with the prevailing literature, as under perfect competition the optimal tax should be equal the marginal damage, whereas under imperfect competition the authority reduces the tax below this given threshold[48]. However, this result is in line with the findings of Brécard (2012) and Lombardini-Riipinen (2005) and can be explained through the assumptions that (i) a consumer buys one unit of quality or nothing, (ii) the market is fully covered[49] and, *ceteris-paribus*, (iii) environmental product quality strictly increases production costs despite the existence of process R&D. If these assumptions are fulfilled, then a lump-sum tax is equivalent to a uniform commodity tax, as noted by Brécard (2008). This establishes the fourth result.

Further, the emission-tax τ_e neither affect the entrepreneur's operating-profits nor impacts product differentiation at the regulated equilibrium.

[48] Refer to Requate (2007) for a recent survey.

[49] Refer to appendix A.8.

7.2 Second-best welfare with process R&D τ_s

As mentioned above, the process R&D subsidy only affects the profits but not the operating-profits of the entrepreneurs. Further, it does not affect product differentiation at the regulated equilibrium. Given, the regulator can only use the R&D subsidy fiscal instrument, welfare defined by equation (6.14) reduces to:

$$\mathcal{W}^{r2} = \mathcal{W}^u + \frac{2(\xi - \rho)\tau_s\left(-5\xi - \rho + 3(\xi + \rho)\tau_s\right)}{9\left(\tau_s - 1\right)^2}. \tag{7.2}$$

Obviously, welfare is increasing in the subsidy rate τ_s beyond the welfare which results for the unregulated economy, given $\tau_s < \frac{5\xi+\rho}{3(\xi+\rho)} = \tau_s^o$ as $\rho > \xi$. Now, based on the first order-condition of the regulator's game, we finally arrive at the single solution $\tilde{\tau}_s = \frac{5\xi+\rho}{\xi+5\rho} < \tau_s^o$ as $\rho > \xi$. This leads to the following result:

Result 5 *Given the absence of administrative costs, the second-best subsidy-rate $\tilde{\tau}_s < \tau_s^o$ ensures that $\mathcal{W}^{r2} > \mathcal{W}^u$. Further, $\mathcal{W}^{r2}$ is strictly increasing in $\tau_s \in (0, \tilde{\tau}_s)$.*

This result has the important policy implication that, given the absence of any further policy instruments, setting the subsidy-rate within the optimal interval defined as $\tau_s \in (0, \tau_s^o]$ always ensures that $\Delta\mathcal{W}^{r2} \equiv \mathcal{W}^{r2} - \mathcal{W}^u > 0$.

7.3 Second-best welfare with pollution tax τ_e and process R&D τ_s

Finally, we discuss the welfare-implications for employing both fiscal instruments, the pollution tax and the process R&D subvention scheme. We can re-express the social optimal welfare $\mathcal{W}^o$ as

$$\mathcal{W}^o = \mathcal{W}^r + \frac{4c(\xi + \rho)^2 + 4\delta^2 + 4\tau_e\left(\tau_e - 2\delta\right) + 1}{8c} + \frac{4(\xi - \rho)^2}{9\left(\tau_s - 1\right)^2} - \frac{2(\xi + 5\rho)(\xi - \rho)}{9\left(\tau_s - 1\right)}, \tag{7.3}$$

which directly motivates the following result:

Result 6 *The combination of both instruments affects the economy's welfare in a positive way but it fails to establish the first-best-optimum.*

Proof. From equation (7.3) we can directly observe that the welfare-difference defined as $\Delta\mathcal{W} \equiv \mathcal{W}^o - \mathcal{W}^r$ is a decreasing function in the arguments τ_e, given $\delta > \tau_e$ and $\tau_s > \frac{5\xi+\rho}{\xi+5\rho}$ as $\rho > \xi$. Irrespective of the regulator's chosen value of τ_e[50], $\Delta\mathcal{W} \equiv \mathcal{W}^o - \mathcal{W}^r$ based on equation (7.3) exhibits a unique minimum at $\tilde{\tau}_s$ for $\tau_s \in (0, 1)$. Although, $\mathcal{W}^{r12}$ is higher compared to $\mathcal{W}^{r1}$ [51] and to $\mathcal{W}^{r2}$ for reasonable parameter-values[52], the first-best optimum $\mathcal{W}^o$ cannot be reached. Given $\tau_e = \delta$, the second-best subsidy-rate $\tilde{\tau}_s < \underline{\underline{\tau_s}}$, with

$$\underline{\underline{\tau_s}} \equiv \frac{\sqrt{(-20c\xi^2+16c\xi\rho+4c\rho^2+36\delta\tau_e-18\tau_e^2)^2-4(9\tau_e^2-18\delta\tau_e)(12c\xi^2-12c\rho^2-18\delta\tau_e+9\tau_e^2)}+20c\xi^2-16c\xi\rho-4c\rho^2-36\delta\tau_e+18\tau_e^2}{2(12c\xi^2-12c\rho^2-18\delta\tau_e+9\tau_e^2)}$$

ensures that $\mathcal{W}^{r12} > \mathcal{W}^u$.

7.4 Efficiency of process R&D subsidy policy

Based on the results derived in the following sections, we can conjecture that given the regulator sets the Pigouvian tax, welfare-outcome crucially depends on the chosen process R&D subsidy rate τ_s, given this additional instrument is available. Based on the derived fifth result of this contribution, we directly deduce that $\mathcal{W}^{r2}$ is strictly increasing given $\tau_s \in (0, \tilde{\tau}_s)$. Further, we can observe that $\mathcal{W}^{r1}$ is strictly higher compared to $\mathcal{W}^{r2}$ given either the regulator sets $\tau_s \in (0, \underline{\tilde{\tau}_s})$ with

$$\underline{\tilde{\tau}_s} \equiv \frac{-\sqrt{(-20c\xi^2+16c\xi\rho+4c\rho^2+36\delta\tau_e-18\tau_e^2)^2-4(9\tau_e^2-18\delta\tau_e)(12c\xi^2-12c\rho^2-18\delta\tau_e+9\tau_e^2)}+20c\xi^2-16c\xi\rho-4c\rho^2-36\delta\tau_e+18\tau_e^2}{2(12c\xi^2-12c\rho^2-18\delta\tau_e+9\tau_e^2)},$$

or the regulator decides to choose $\tau_s \in (\overline{\tilde{\tau}_s}, \underline{\underline{\tau_s}})$. Hence, setting $\tau_s \in (\tau_s^o, 1)$ directly results in a welfare-loss $\mathcal{W}^{r12} - \mathcal{W}^{r1} < 0$ compared to a policy where the authority only decides over the environmental tax τ_e. Hence, this model contributes to the literature regarding the efficiency of R&D policy programs.

Figure 7.1 graphically confirms the previously derived results[53]. The gray shaded areas reflect the welfare-gains employing an efficient R&D subsidy policy with or without

[50] Inserting $\tau_s = \frac{5\xi+\rho}{\xi+5\rho}$ in equation (7.3) leads to $\Delta\mathcal{W} = \frac{2c\left(17\xi^2+26\xi\rho-7\rho^2\right)+36\delta^2+36\tau_e(\tau_e-2\delta)+9}{72c}$ which is positive for all $\tau_e \in (0, \infty^+)$ and realizes a global minimum at $\tau_e = \delta$.

[51] This argument can be shown as follows. Define $\Delta\mathcal{W}^{r12r1} \equiv \mathcal{W}^{r12} - \mathcal{W}^{r1} = \frac{2(\xi-\rho)\tau_s(-5\xi-\rho+3(\xi+\rho)\tau_s)}{9(\tau_s-1)^2}$, which is strictly positive, given $\tau_s \in (0; \tau_s^o)$ and $\rho > \xi$ per assumption.

[52] This second argument can be shown as follows. Define $\Delta\mathcal{W}^{r12r2} \equiv \mathcal{W}^{r12} - \mathcal{W}^{r2} = \frac{\tau_e(2\delta-\tau_e)}{2c}$, which is strictly positive, given $\tau_e < 2\delta$ and $\rho > \xi$ per assumption. Given the second-best environmental tax $\delta = \tau_e$, we finally arrive at $\mathcal{W}^{r12} - \mathcal{W}^{r2} = \frac{\delta^2}{2c} > 0$.

[53] The following parameter values have been used to construct figure 4.1: $\delta = 0.2$, $c = 1.0$, $\bar{e} = 3.0$, $\bar{\theta} = 5.0$, $\xi = 0.1$, $\rho = 0.7$ and $\tau_e = \delta$.

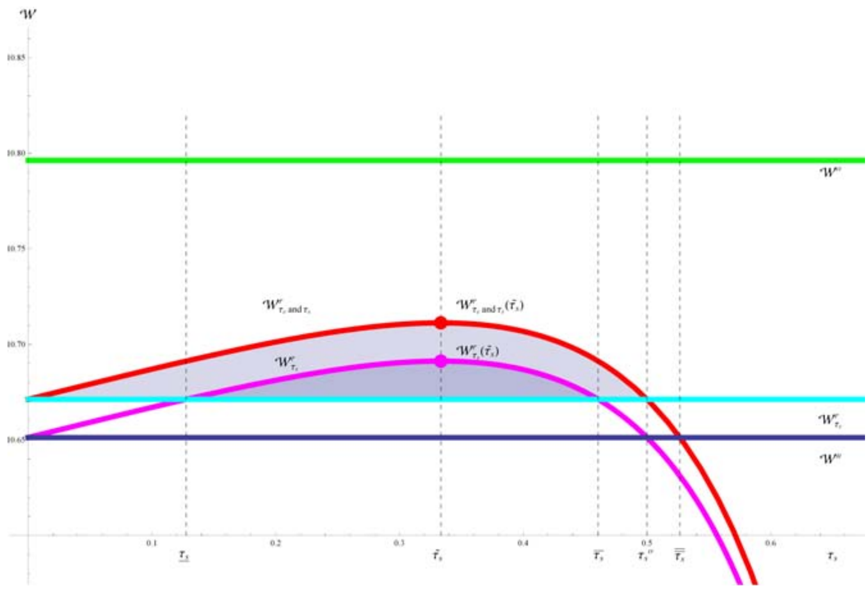

Figure 7.1: Environmental policy evaluation

imposing the optimal environmental tax policy, which consists of setting the Pigouvian tax. Obviously, in terms of welfare-gains, introducing a policy which is based on imposing solely the Pigouvian tax outperforms a process R&D subsidy policy, given the R&D subsidy-rate is set below $\underline{\tau_s}$ or is set beyond $\overline{\tau_s}$. The combination of both instruments is always welfare-increasing compared to the unregulated solution, given the subsidy-rate does not exceed the social-optimal process R&D subsidy rate τ_s^o.

8 Conclusion

In this paper we propose a novel framework discussing the interplay of process R&D activities, the price and environmental quality setting of heterogeneous entrepreneurs in a market where consumers feel up to paying for environmental's quality of a vertically differentiated good. To the best of our knowledge, this is the first time that this kind of an undoubtedly, highly-policy relevant interplay is discussed thoroughly in the context of the strategic industrial organization literature.

By solving for the unregulated and decentralized equilibrium, we decompose an entrepreneur's incentive conducting process R&D in four parts. In particular we show that an entrepreneur's incentive of conducting own process R&D, which reduces production costs and hence increases welfare, is reduced due to the existence of knowledge-spillovers. Moreover, due to the strategic complementarities, both in prices as well as in environmental quality, a strategic effect reinforces the negative consequences of the spillover-effect. In particular we show that this negative knowledge-spillover externality is internalized by the social planer. Consequently, the question arises which fiscal-policy-mix is optimal in order to establish a first-best solution.

We have identified that a mix of an *ad-valorem* tax, an imposed emission tax and an appropriate R&D subsidy scheme establishes the first-best-solution. However, as in reality only a sub-set of (appropriate) policy instruments is available, we further thoroughly discuss the implementation of a second-best solution. After demonstrating that the *ad-valorem* tax in general reduces environmental quality, in the following we directly focus on a second-best solution consisting of a combination of the emission tax and the R&D subsidy scheme or relying either only on the R&D subsidy-scheme or on the emission tax. We find that the second-best solution consisting of a combination of the emission tax and the R&D subsidy-scheme is, compared to the unregulated solution, welfare-increasing but fails to establish the first-best optimum. We further address the question whether a R&D subsidy policy is unconditionally efficient with respect to welfare-gains. We find that this is not the case by identifying a parameter-space for the subsidy-rate which guarantees welfare-gains by increasing the process R&D subsidy-rate, given the environmental tax is equal to the Pigouvian tax.

Even if our model has the merit to offer an analytical solution of the imposed three-step game from which we can derive several implications for environmental policy interventions, however it first defines the starting-point for several further research projects in this direction. In order to extend this paper's analysis, it may be useful to expand the model by simultaneously discussing the interplay of both product as well as process R&D activities. For instance, in contrast to our model, the existence of R&D in environmental product quality may directly affect product differentiation. In this context, it may be also useful to introduce uncertainty with respect to the product and process R&D activities. Further, it may be interesting to generalize the model for the case of an uncovered market. In a nutshell, it seems that a generalization of this setup requires simulation methods, as an analytical solution cannot be guaranteed.

9 Appendix

A.1 Proof of the sub-game quality equilibrium for the unregulated economy

In section 4.2. we have mentioned that only one quality vector (q_g, q_b) fulfills the second-order conditions and further guarantees a positive operating-profit for each entrepreneur. The solution of the system of two equations and degree two in produced quality levels $q_g > q_b$, which is based on equation (4.1) with $\frac{\partial \pi_i(q_i,q_j,\chi_i,\chi_j)}{\partial q_i}|_{(p_i^*,p_j^*)} = 0$ for $i = \{b, g\}$ and $i \neq j$ produces five pairs of potential quality vector equilibria. Now it is easy to show that only one solution denoted by (q_g^*, q_b^*) generates positive operating profits for both entrepreneurs. This solution is represented with equations (4.4) and (4.5).

Lemma 1. *The single solution (q_g^*, q_b^*) fulfills the second-order conditions:*

$$\frac{\partial^2 \pi_g(p_g, q_g, \chi_g, \chi_b)}{\partial q_g^2}|_{(q_g^*,q_b^*)} = \frac{1}{972} c\,(8c(\xi-\rho)(\chi_g-\chi_b)-9)(8c(\xi-\rho)(\chi_g-\chi_b)+27) \leq 0$$
$$\frac{\partial^2 \pi_b(p_g, q_g, \chi_g, \chi_b)}{\partial q_b^2}|_{(q_g^*,q_b^*)} = \frac{1}{972} c\,(8c(\xi-\rho)(\chi_g-\chi_b)-27)(8c(\xi-\rho)(\chi_g-\chi_b)+9) \leq 0,$$

Proof. Given $\chi_g \in \left[\frac{9}{8c(\xi-\rho)} + \chi_b; \frac{9}{8c(\rho-\xi)} + \chi_b\right]$, for $\rho > \xi$, $i = \{g, b\}$ with $i \neq j$, the second-order conditions are fulfilled. □

Further, the *Routh-Hurwitz stability condition* evaluated at the equilibrium (q_g^*, q_b^*) is satisfied, given $\left(\frac{\partial^2\pi_i(\cdot)}{\partial q_i^2}\frac{\partial^2\pi_j(\cdot)}{\partial q_j^2}\right) - \left(\frac{\partial^2\pi_i(\cdot)}{\partial q_i \partial q_j}\frac{\partial^2\pi_j(\cdot)}{\partial q_j \partial \chi_i}\right) = -\frac{c^2(8c(\xi-\rho)(\chi_g-\chi_b)-9)(8c(\xi-\rho)(\chi_g-\chi_b)+9)}{1458} \equiv \Xi > 0$. The latter argument can be shown as follows: First, note that Ξ is strictly globally concave. It is increasing in the interval $\chi_g \in \left(\frac{9}{8c(\xi-\rho)} + \chi_b, \chi_b\right)$. At $\chi_g = \chi_b$ it reaches a global maximum. For $\chi_g \in \left(\chi_b; \frac{9}{8c(\rho-\xi)} + \chi_b\right)$, Ξ is strictly decreasing. For $\chi_g = \left(\frac{9}{8c(\xi-\rho)}\right) + \chi_b$ and $\chi_g = \left(\frac{9}{8c(\rho-\xi)}\right) + \chi_b$, respectively, Ξ turns out to be zero. Hence, the equilibrium (q_g^*, q_b^*) represented with equations (4.4) and (4.5) offers a unique and stable interior solution for $\chi_g \in \left(\frac{9}{8c(\xi-\rho)} + \chi_b; \frac{9}{8c(\rho-\xi)} + \chi_b\right)$. As can be seen further, $\frac{\partial^2\pi_g(p_g,q_g,\chi_g,\chi_b)}{\partial q_g^2}|_{(q_g^*,q_b^*)} = \frac{\partial^2\pi_b(p_g,q_g,\chi_g,\chi_b)}{\partial q_b^2}|_{(q_g^*,q_b^*)}$ for $\chi_g = \chi_b$.

Moreover, the equilibrium represented by (q_g^*, q_b^*) has to fulfill the non-deviation conditions indeed being a Nash-equilibrium. These are given as:

$$\pi_g^o(q_g^*, q_b^*) \geq \pi_g^o(q_g, q_b^*), \text{ for } q_g \in [0, \bar{e}] \tag{9.1}$$
$$\pi_b^o(q_g^*, q_b^*) \geq \pi_g^o(q_g^*, q_b), \text{ for } q_g \in [0, \bar{e}]. \tag{9.2}$$

First, we focus on equation (9.1). We notice that $\pi_g^o(q_g, q_b^*)$ is strictly positive, given $n_g(q_g, q_b^*) \in (0, 1]$. Now let us define $\underline{q}_g|_{n_g(q_g^*,q_b^*)=1} = \frac{2\bar{\theta}-1}{2c}$ and further $\overline{q}_g|_{n_g(q_g^*,q_b^*)=0} = -\frac{\sqrt{c^2(8c(\xi-\rho)(\chi_b-\chi_g)+9)-2c(\bar{\theta}+1)}}{2c^2}$, both representing a corner solution each.

Given $q_g \in (\underline{q}_g|_{n_g(q_g^*,q_b^*)=1}; \overline{q}_g|_{n_g(q_g^*,q_b^*)=0})$, $\pi_g^o(q_g, q_b^*)$ exhibits a global maximum at $q_g^* \in (\underline{q}_g|_{n_g(q_g^*,q_b^*)=1}; \overline{q}_g|_{n_g(q_g^*,q_b^*)=0})$. The latter argument is true as $\underline{q}_g|_{n_g(q_g^*,q_b^*)=1} < q_g^* < \overline{q}_g|_{n_g(q_g^*,q_b^*)=0}$ with $q_g^* = \frac{12\bar{\theta}+8c(\xi-\rho)(\chi_g-\chi_b)+3}{12c}$ and $\chi_g \in \left(\frac{9}{8c(\xi-\rho)} + \chi_b; \frac{9}{8c(\rho-\xi)} + \chi_b\right)$.

Hence, $n_g(q_g^*, q_b^*) \in (0, 1)$. Now, for $q_g \in (\overline{q}_g|_{n_g(q_g^*,q_b^*)=0}); \infty^+)$, it directly follows that $n_g(q_g, q_b^*) < 0$. Moreover, for $q_g \in (0; \underline{q}_g|_{n_g(q_g^*,q_b^*)=1})$, we obtain $n_g > 1$. Finally, with $q_g \in (\underline{q}_g|_{n_g(q_g^*,q_b^*)=1}; \overline{q}_g|_{n_g(q_g^*,q_b^*)=0}) \leq \bar{e}$, we can deduce that $\pi_g^o(q_g^*, q_b^*) \geq \pi_g^o(q_g, q_b^*)$.
Second, we turn to equation (9.2). As the same arguments hold for the brown quality producing entrepreneur, we skip the proof.

As shown in chapter 3.2, inserting equations (4.4) and (4.5) in the operating profits functions represented by equation (4.1) results in positive operating profits for both entrepreneurs, given by equations (4.8) and (4.9). □
Thus, the equilibrium (q_g^*, q_b^*) represented by equations (4.4) and (4.5) is indeed a stable, interior solution, which fulfills the non-deviation conditions for both entrepreneurs.

A.2 Proof of proposition 2

The equilibrium given by equation (4.12) offers a unique and stable interior solution, if it meets three conditions listed in proposition 2. We prove the conditions sequentially.

Condition 1: The second-order conditions for profit maximization represented by equation (4.13) are fulfilled.
Proof: It is straightforward to show that the second order conditions represented by equation (4.13) are fulfilled, if we assume that $\rho \in \left(0, \frac{3\sqrt{\frac{3}{2}}}{4\sqrt{c}}\right)$ and $\rho > \xi$ per assumption. □

Condition 2: The Routh-Hurwitz stability condition which requires

$$\left(\frac{\partial^2\pi_i(\cdot)}{\partial\chi_i^2}\frac{\partial^2\pi_j(\cdot)}{\partial\chi_j^2}\right)-\left(\frac{\partial^2\pi_i(\cdot)}{\partial\chi_i\partial\chi_j}\frac{\partial^2\pi_j(\cdot)}{\partial\chi_j\partial\chi_i}\right)>0. \tag{9.3}$$

Proof: After conducting some algebraic manipulations by employing equations (4.10) and (4.11), the *Routh-Hurwitz* stability condition can be rewritten as $\frac{1}{27}\left[27-32(\xi-\rho)^2\right]$ which is strictly positive, given $\rho \in \left(0, \frac{3\sqrt{\frac{3}{2}}}{4\sqrt{c}}\right)$ and $\rho > \xi$ per assumption. $\square$

Condition 3: The R&D outcomes are strictly positive, that is, $\chi_i > 0$ *for* $i \neq j$.
Proof: From equation (4.12) we can directly deduce that $\chi_i > 0$ for $i \neq j$, given $\rho > \xi$ per assumption. $\square$

A.3 Proof of the non-deviation conditions for the unregulated economy's process R&D sub-game equilibrium

For the unregulated economy, please set $\tau_v = 1$ and $\tau_s = 0$. Further set $\pi_i^r(\cdot) = \pi_i(\cdot)$, $\pi_i^{*r}(\cdot) = \pi_i^*(\cdot)$, $\chi_i^r = \chi_i$ and $\chi_i^{r*} = \chi_i^*$ for $i = \{g, b\}$ and $i \neq j$. Then follow the proof given in A.4.

A.4 Proof of the non-deviation conditions for the regulated economy's process R&D sub-game equilibrium

The equilibrium represented by (χ_g^*, χ_b^*) has to fulfill the non-deviation conditions. These conditions are given as:

$$\pi_g^r(\chi_g^{*r}, \chi_b^{*r}) \geq \pi_g(\chi_g^r, \chi_b^{*r}), \text{ for } \chi_g^r \geq 0 \tag{9.4}$$

$$\pi_b^r(\chi_g^{*r}, \chi_b^{*r}) \geq \pi_g(\chi_g^{*r}, \chi_b^r), \text{ for } \chi_b^r \geq 0. \tag{9.5}$$

First, we focus on equation (9.4) and further make use of the following Lemma.

Lemma 2. $\pi_g^r(\chi_g^{r*}, \chi_b^{r*})$ *is strictly positive for* $\rho \in \left(0, \frac{3\sqrt{\frac{3}{2}}(1-\tau_s)}{4\sqrt{c(1-\tau_s)\tau_v^2}}\right)$.

Proof. We notice that $\pi_g(\chi_g^{r*}, \chi_b^{r*})$ is strictly positive with $\pi_g(\chi_g^{r*}, \chi_b^{r*}) = \frac{3}{8c\tau_v^2} + \frac{2(\xi-\rho)^2}{9(\tau_s-1)}$, given the operating-profit $\pi^{or}(\cdot) = \frac{3}{8c\tau_v^2}$ exceeds $\frac{2(\xi-\rho)^2}{9(\tau_s-1)} < 0$. Now $\pi^{or}(\cdot) > \frac{2(\xi-\rho)^2}{9(\tau_s-1)}$, given $\rho \in \left(0, \frac{3\sqrt{3}(1-\tau_s)}{4\sqrt{c(1-\tau_s)\tau_v^2}}\right)$. Appendix A.6 tells that the equilibrium represented by equation (6.10) is a unique and interior solution, given $\rho \in \left(0, \frac{3\sqrt{\frac{3}{2}}(1-\tau_s)}{4\sqrt{c(1-\tau_s)\tau_v^2}}\right)$. As the upper limit $\frac{3\sqrt{3}(1-\tau_s)}{4\sqrt{c(1-\tau_s)\tau_v^2}}$ exceeds the upper limit $\frac{3\sqrt{\frac{3}{2}}(1-\tau_s)}{4\sqrt{c(1-\tau_s)\tau_v^2}}$ as $\frac{3\sqrt{3}\left(2-\sqrt{2}\right)(1-\tau_s)}{8\sqrt{c(1-\tau_s)\tau_v^2}} > 0$, we straightforwardly conclude that $\pi_g^r(\chi_g^{r*}, \chi_b^{r*})$ is strictly positive for $\rho \in \left(0, \frac{3\sqrt{\frac{3}{2}}(1-\tau_s)}{4\sqrt{c(1-\tau_s)\tau_v^2}}\right)$. □

Now for $\chi_g^r \in \left(\frac{9}{8c(\xi-\rho)\tau_v^2} + \chi_b^r; \chi_g^{r*}\right)$, $\pi_g^r(\chi_g^r, \chi_b^{r*})$ is strictly increasing with χ_g^r. For $\chi_g^r \in \left(\chi_g^{r*}; \frac{9}{8c(\rho-\xi)\tau_v^2} + \chi_b\right)$, $\pi_g^r(\chi_g^r, \chi_b^{*r})$ is strictly decreasing with χ_g^r. For $\chi_g^r = \chi_g^{*r}$, $\pi_g^r(\chi_g^r, \chi_b^{*r})$ offers an unique global maximum with $\pi_g^r(\chi_g^r, \chi_b^{*r})|_{\chi_g^r=\chi_g^{*r}} = \pi_g^r(\chi_g^{r*}, \chi_b^{r*})$. □
Hence, the process R&D equilibrium outcome represented with equation (4.12) or (6.10), respectively, fulfills the non-deviation conditions.

A.5. Decomposition of process R&D incentives for the unregulated economy

Differentiating the first-order conditions of the second stage of the game with respect to χ_i, we obtain

$$\begin{pmatrix} \frac{\partial^2 \pi_i^o}{\partial q_i^2} & \frac{\partial^2 \pi_i^o}{\partial q_i \partial q_j} \\ \frac{\partial^2 \pi_j^o}{\partial q_j \partial q_i} & \frac{\partial^2 \pi_j^o}{\partial q_j^2} \end{pmatrix} \begin{pmatrix} \frac{\partial q_i}{\partial \chi_i} \\ \frac{\partial q_j}{\partial \chi_i} \end{pmatrix} = \begin{pmatrix} \frac{2}{9}c(\xi-\rho) \\ \frac{2}{9}c(\xi-\rho) \end{pmatrix}, \tag{9.6}$$

for $i \neq j$. From this expression we directly calculate

$$\frac{\partial q_j}{\partial \chi_i} = \left[\frac{\frac{2}{9}c(\rho-\xi)}{\left(\frac{\partial^2\pi_i(\cdot)}{\partial q_i^2}\frac{\partial^2\pi_j(\cdot)}{\partial q_j^2}\right) - \left(\frac{\partial^2\pi_i(\cdot)}{\partial q_i \partial q_j}\frac{\partial^2\pi_j(\cdot)}{\partial q_j \partial q_i}\right)}\right]\left(\frac{\partial^2 \pi_j^o}{\partial q_j \partial q_i} - \frac{\partial^2 \pi_i^o}{\partial q_i^2}\right), \tag{9.7}$$

with $\left(\frac{\partial^2\pi_i(\cdot)}{\partial q_i^2}\frac{\partial^2\pi_j(\cdot)}{\partial q_j^2}\right) - \left(\frac{\partial^2\pi_i(\cdot)}{\partial q_i \partial q_j}\frac{\partial^2\pi_j(\cdot)}{\partial q_j \partial q_i}\right) \equiv \Xi > 0$ as shown in A.1. Inserting equation (9.7) in the first line of equation (4.21) results in the second line of equation (4.21). To conserve space, we further introduce an indicator function $\vartheta = 1\boldsymbol{I}_{[i=h]} - 1\boldsymbol{I}_{[i=b]}$ to differentiate between the green ($\vartheta = 1$) and brown entrepreneur ($\vartheta = -1$) with $i = \{g, b\}$ and $i \neq j$. □

A.6 Proof of the sub-game quality equilibrium for the regulated economy

To prove that only one quality vector (q_g^r, q_b^r) fulfills the second-order conditions and further guarantees a positive operating-profit for each entrepreneur for the regulated economy, we follow the same steps as used for the proof of proposition 2 given in appendix A.1.

Lemma 3. *The solution of the two-dimensional system of degree two in the produced environmental product quality, denoted as (q_g^{*r}, q_b^{*r}), which is now derived from equation (6.1), fulfills the the second order conditions:*

$$\frac{\partial^2 \pi_g^r(p_g^r, q_g^r, \chi_g^r, \chi_b^r)}{\partial q_g^{r2}}|_{(q_g^{r*}, q_b^{r*})} = \frac{1}{972}c\left(16c(\xi-\rho)\tau_v^2\left(\chi_g^r-\chi_b^r\right)\left(4c(\xi-\rho)\tau_v^2\left(\chi_g^r-\chi_b^r\right)+9\right)-243\right) \leq 0$$
$$\frac{\partial^2 \pi_b^r(p_g^r, q_g^r, \chi_g^r, \chi_b^r)}{\partial q_b^{r2}}|_{(q_g^{r*}, q_b^{r*})} = \frac{1}{972}c\left(16c(\xi-\rho)\tau_v^2\left(\chi_g^r-\chi_b^r\right)\left(4c(\xi-\rho)\tau_v^2\left(\chi_g^r-\chi_b^r\right)-9\right)-243\right) \leq 0,$$

Proof. Given $\chi_g^r \in \left[\frac{9}{8c(\xi-\rho)\tau_v^2}+\chi_b^r; \frac{9}{8c(\rho-\xi)\tau_v^2}+\chi_b^r\right]$, for $\rho > \xi$ and $i = \{g, b\}$ with $i \neq j$.□

The *Routh-Hurwitz stability condition* evaluated at the regulated equilibrium (q_g^{*r}, q_b^{*r}) is satisfied as $\left(\frac{\partial^2 \pi_i(\cdot)^r}{\partial q_i^{r2}} \frac{\partial^2 \pi_j(\cdot)^r}{\partial q_j^{r2}}\right) - \left(\frac{\partial^2 \pi_i(\cdot)^r}{\partial q_i^r \partial q_j^r} \frac{\partial^2 \pi_j(\cdot)}{\partial q_j^r \partial q_i^r}\right) = -\frac{c^2\left(64c^2(\xi-\rho)^2\tau_v^4\left(\chi_g^r-\chi_b^r\right)^2-81\right)}{1458} \equiv \Xi^r > 0$ for $\chi_g^r \in \left(\frac{9}{8c(\xi-\rho)\tau_v^2}+\chi_{b^r}; \frac{9}{8c(\rho-\xi)\tau_v^2}+\chi_b^r\right)$ with Ξ^r being strictly globally concave with a global maximum realized at $\chi_g^r = \chi_b^r$. Moreover, the equilibrium represented by (q_g^{*r}, q_b^{*r}) has to fulfill the non-deviation conditions. These are given as:

$$\pi_g^r(q_g^{*r}, q_b^{*r}) \geq \pi_g^r(q_g^r, q_b^{*r}), \text{ for } q_g^r \in [0, \bar{e}] \tag{9.8}$$
$$\pi_b^r(q_g^{*r}, q_b^{*r}) \geq \pi_g^r(q_g^{*r}, q_b^r), \text{ for } q_g^r \in [0, \bar{e}]. \tag{9.9}$$

For $n_g^r(q_g^r, q_b^{*r}) \in (0, 1]$, we observe that $\pi_g^r(q_g^r, q_b^{*r})$ is strictly positive. Let $\underline{q}_g|_{n_g^r(q_g^{r*}, q_r^{r*})=1} = \frac{2\bar{\theta}+2\tau_e\tau_v-1}{2c\tau_v}$ and $\overline{q}_g|_{n_g^r(q_g^*, q_b^*)=0} = \frac{2c\tau_v\left(\bar{\theta}+\tau_e\tau_v+1\right)+\sqrt{c^2\tau_v^2(9-8c(\xi-\rho)\tau_v^2(\chi_g-\chi_b))}}{2c^2\tau_v^2}$ both representing a corner solution each.
Given $q_g^r \in (\underline{q}_g^r|_{n_g^r(q_g^{*r}, q_b^{*r})=1}; \overline{q}_g^r|_{n_g^r(q_g^{*r}, q_b^{*r})=0})$, $\pi_g^r(q_g^r, q_b^{*r})$ exhibits a global maximum at $q_g^{*r} \in (\underline{q}_g^r|_{n_g^r(q_g^*, q_b^*)=1}; \overline{q}_g^r|_{n_g^r(q_g^*, q_b^*)=0})$, as one can show that $\underline{q}_g^r|_{n_g^r(q_g^{*r}, q_b^{*r})=1} < q_g^{*r} < \overline{q}_g^r|_{n_g^r(q_g^{*r}, q_b^{*r})=0}$ with $q_g^{*r} = \frac{12\bar{\theta}+8c(\xi-\rho)\tau_v^2\left(\chi_g^r-\chi_b^r\right)+12\tau_e\tau_v+3}{12c\tau_v}$ and $\chi_g^r \in \left(\frac{9}{8c(\xi-\rho)\tau_v^2}+\chi_b^r; \frac{9}{8c(\rho-\xi)\tau_v^2}+\chi_b^r\right)$. Now, for $q_g^r \in (\overline{q}_g^r|_{n_g^r(q_g^{*r}, q_b^{*r})=0}); \infty^+)$, it directly follows that $n_g^r(q_g^r, q_b^{*r}) < 0$. Moreover, for $q_g^r \in (0; \underline{q}_g^r|_{n_g^r(q_g^{*r}, q_b^{*r})=1})$, we obtain $n_g^r > 1$. Finally, with $q_g^r \in (\underline{q}_g^r|_{n_g^r(q_g^{*r}, q_b^{*r})=1}; \overline{q}_g^r|_{n_g^r(q_g^{*r}, q_b^{*r})=0}) \leq \bar{e}$, we can deduce that $\pi_g^r(q_g^{*r}, q_b^{*r}) \geq \pi_g^r(q_g^r, q_b^{*r})$. Thus, the equilibrium represented by

(q_g^{*r}, q_b^{*r}) for the regulated economy establishes an interior solution with $n_g^r(q_g^{*r}, q_b^{*r}) \in (0,1)$.
Second, we turn to equation (9.2). As the same arguments hold for the low quality producing entrepreneur, we skip the proof.

Inserting equations (6.2) and (6.3) in the operating profits functions represented by equation (6.1) results in positive operating profits for both entrepreneurs which are now represented with equations (6.6) and (6.7). $\square$

In a nutshell, the quality equilibrium on stage two, (q_g^{r*}, q_b^{r*}), represented by equations (4.4) and (4.5) is a stable, interior solution. Further, the non-deviation conditions for both entrepreneurs are fulfilled.

A.7 Full market coverage for the unregulated equilibrium

As mentioned in this paper, full market coverage is guaranteed, given $\hat{\theta} \leq \underline{\theta} = \overline{\theta} - 1$. Using equations (4.4) and (4.3) together with equation (4.12), full market coverage is guaranteed, if and only if

$$\overline{\theta} \geq 1 + \frac{\sqrt{64c(\xi - \rho)(\xi + \rho) + 75}}{4\sqrt{3}} = 1 + \Theta^u, \tag{9.10}$$

with $\Theta^u \equiv \frac{\sqrt{64c(\xi-\rho)(\xi+\rho)+75}}{4\sqrt{3}}$. Now, it is straightforward to show that $\frac{\partial\Theta(\cdot)}{\partial\rho} < 0$ and $\frac{\partial\Theta(\cdot)}{\partial\xi} > 0$ with $\xi < \rho$ and $\rho \in \left(0, \frac{3\sqrt{\frac{3}{2}}}{4c}\right)$. Hence, $\bar{\theta}$ decreases with the R&D efficiency parameter ρ but increases with the knowledge-spillover parameter ξ. Assuming for a moment that $\xi = \rho = 0$, equation (9.10) reduces to $\bar{\theta} \geq \frac{9}{4}$ which is in line with the findings made by Ecchia and Lambertini (1998), who show that for $\bar{\theta} \geq \frac{9}{4}$ a pure-strategy and sub-game perfect equilibrium exists which guarantees full market coverage. Suppose now, for $\rho = \frac{3\sqrt{\frac{3}{2}}}{4c}$ equation (9.10) changes to $\overline{\theta} \geq \frac{1}{4}\sqrt{\frac{64c\xi^2}{3} + 7} + 1$. Hence, for $\forall\, \xi < \rho \in \left(0, \frac{3\sqrt{\frac{3}{2}}}{4c}\right)$, $\overline{\theta} \geq 1.66144$ establish a pure-strategy and sub-game perfect equilibrium which is in line with full market coverage.

A.8 Full market coverage for the regulated equilibrium

For the regulated economy, the condition for full market coverage turns out to be

$$\bar{\theta} \geq \frac{1}{4}\sqrt{\frac{640\tau_v^2\left(3\bar{e}\tau_e\left(\tau_s-1\right)-2(\xi-\rho)(\xi+\rho)\right)}{3\left(\tau_s-1\right)}+25}-\tau_e\tau_v+1=1+\Theta^r, \tag{9.11}$$

with $\Theta^r \equiv \frac{1}{4}\sqrt{\frac{640\tau_v^2(3\bar{e}\tau_e(\tau_s-1)-2(\xi-\rho)(\xi+\rho))}{3(\tau_s-1)}+25}-\tau_e\tau_v$. Equation (9.11) results if we use equations (6.3) and (4.12). Now, increasing the emission tax τ_e, *ceteris paribus*, this policy tends to increase the threshold $\bar{\theta}$ for $\tau_e \in (0, \bar{\tau}_e)$ with $\bar{\tau}_e \equiv \frac{3840\bar{e}^2+\frac{256(\xi-\rho)(\xi+\rho)}{\tau_s-1}-\frac{15}{\tau_v^2}}{384\bar{e}}$ but decreases for $\tau_e \in (\bar{\tau}_e, \infty^+[$. Further, the threshold increases with the *ad-valorem* tax τ_v, which is in line with the findings made by Brécard (2012) and decreases with the process R&D subsidy rate τ_s. If the menu of policy instruments is set to $\{\tau_s, \tau_e, \tau_v\} = \{0, 0, 1\}$, equation (9.11) directly reduces to equation (9.10).

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