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ENVIRONMENTAL QUALITY COMPETITION AND ECO-LABELING****

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ABSTRACT: A three-stage game including investments, environmental quality provision and price competition is developed to study the impact of green technology investment (ecolabeling), in a duopoly model of vertical product differentiation. The firms' incentives to invest in green technologies depend on their relative cost structure. When firms are identical with respect to fixed costs, both firms will always invest, but if one firm is more efficient in investing, then the other firm may or may not invest depending on the level of unit cost of investment. Quality competition will be tighter when the low quality firm is more efficient, and looser when the high quality firm is more efficient in investing. Socially optimal investment for both firms is always positive, but lower than in the duopoly solution. In the absence of environmental externalities, the quality dispersion chosen by profit maximizing firms may be too high or too low, while environmental externalities increase the possibility of too low quality dispersion in the market solution. Finally, and importantly, ecolabeling can be used as a means of reducing excessive investment and increasing too low environmental quality.

Keywords*:* product differentiation, technology investment, socially optimal quality and investments.

JEL classification: *L13, H23, Q20.*

1 INTRODUCTION

Consumer preference to purchase from "green" firms is well established and often revealed through increased willingness to pay for products viewed as "clean," i.e., produced with environmentally-friendly production or abatement technologies such as recycling and use of less polluting inputs. From a polluting firm's perspective, there may be strong incentives to invest in these technologies if public opinion becomes more favorable toward the firm, or if the firm can use its investment as a way of differentiating its product.

Investment in environmentally clean technologies has recently given firms the right to attach a specific "ecolabel" to their product. Well-known examples include dolphin-safe tuna, green electricity, recycling in production processes, organic food production, and production of biodegradable washing powders (e.g., see Sterner [34, Ch. 2], and Nunes and Riyanto [26] for a review of ecolabeling and related green technology investments). Such ecolabels are potentially important strategic variables for firms, serving to differentiate a firm's product from those produced by firms that do not make the necessary green investments. This suggests that environmental quality competition might be studied within the framework of product quality models. These models usually follow a duopoly framework under the assumption of vertical product differentiation. Another common assumption is that firms compete in two stages, first by choosing product quality, and then by choosing prices for their (quality-differentiated) products.

The quality competition literature omits one crucial implication of existing eco-labeling systems, namely investment.[1] Current ecolabeling systems, such as Green Seal in the United States, the Nordic Swan in Scandinavia, the European Union Eco-Label Award Scheme, the Blue Angel in Germany or the Japanese Eco-Mark, are usually designed to cover from 5 to 20 per cent of the market. The license to use the ecolabel is quite often limited to a relatively short period of time. What is most important, however, is the fact that the criteria for ecolabeling rights are revised, i.e. tightened, on average every three or four years (for a representation of these and other eco-labeling schemes, see OECD [27]). This feature of eco-labeling systems implies that any firm, wishing to provide high enough environmental quality

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1 Crampes and Hollander [12] and Ronnen [30] provide studies of general quality models, and see Arora and Gangopadhyay [4] and Arora and Carson [5] for application to environmental quality. There are only a few analytical treatments on eco-labeling, despite that it is becoming more and more common among industries. Matto and Singh [19] discuss circumstances under which eco-labels are profitable to firms, and Swallow and Sedjo [35] provide a graphical analysis of mandatory eco-labeling. There is also a growing non-analytical discussion concerning 'green labeling' in natural resource markets (Kiker and Putz [18], Ozanne and Smith [28]), and empirical analysis of the values of the ecolabel (Nimon and Beghin [25]).

to secure an ecolabel, is forced to make investments to improve quality (and to reduce the costs of quality production). High provision of environmental quality therefore requires some combination of new advanced abatement technologies and increased abatement efforts. These investments are typically costly in terms of either the capital outlays required or the auditing and license costs incurred by the firms. Understanding the inherent dynamics of ecolabeling schemes requires an investigation of firms' investment decisions, and the role of this investment in the competition and product differentiation among firms.

The purpose of this paper is to examine eco-labeling within a vertically differentiated market model. To capture features of ecolabeling discussed above, we extend the usual duopoly model of vertical product differentiation with variable costs and full market coverage by including an initial technology investment stage. This allows us to compare socially optimal levels of investments and environmental qualities with those that result from profit maximization.[2] In addition, we study how externalities, associated with inefficient average environmental quality, affect socially optimal provision of environmental quality. Finally, utilizing an approach used to study the role of advertising in the industrial organization literature (Dixit and Norman [15]), we extend the model by allowing consumer willingness to pay to depend on investments made by firms.

We show that firms' incentives to invest in technologies (and obtain ecolabels) depend crucially on the differences in cost structures between firms. When firms are identical with respect to fixed costs, both firms will always invest in the green technology. If the high quality firm is more effective at the margin in investing (so that the fixed costs differ), then it invests, but the low quality firm may or may not invest depending on the unit cost of investment. The opposite holds if the low quality firm is more efficient in investing.

These different incentives to invest lead to strikingly different outcomes for the provision of environmental quality in markets. In fact, quality competition will be more intense when the low quality firm is more efficient at investment, and less intense when the high quality firm is more efficient at investment. Between these extremes, i.e., when the firms are equally efficient in investing, we arrive at results obtained in the basic two stage model of

[2] There has been some work in product differentiation that considers a three-stage game, but in these models firms' entry decisions represent the first stage, followed by quality and price competition (Cremer and Thisse [13], Shaked and Sutton [31], Lahmandi-Ayed [19]). Our model is loosely related to Zhou et al. [37], who model investment within the traditional two-stage game of product differentiation. In their model, however, investment is not observationally defined and is lumped together with quality into a single composite variable. Unlike Zhou et al. [37], our approach allows an explicit examination of the impact of firms' incentives to invest in technologies used to produce quality. Our model also allows a comparison of incentives to invest between profit maximizing and socially optimal outcomes. These new extensions are important, yet unexplored, issues from the perspective of ecolabeling systems, as they provide insight into the welfare effects of ecolabeling schemes.

quality competition by Crampes and Hollander [12].[3] Thus, the two-stage model of price and quality competition between identical firms is simply a special case of our three-stage model.

Relative to the social optimum, previous work demonstrates that duopolists usually over-invest in order to mitigate price competition. In the absence of externalities, if the firms have identical cost structures, we find that quality dispersion between products chosen by profit maximizing firms is too high, but average quality is too low from the viewpoint of social welfare. But if the high quality firm is more efficient in investment, then quality dispersion and average quality are both too low. This is because the high quality firm may under-provide environmental quality, while the low quality firm always under-provides environmental quality. This possibility is increased by the presence of environmental externalities. These findings represent an important departure from the two-stage quality competition literature. For our problem here, they imply that ecolabeling can be used as a means of reducing excessive investment and increasing environmental quality.

The rest of the paper is structured as follows. In Section 2 we develop a duopoly model of vertical product differentiation, and analyze price, quality and investment stages. In Section 3 we examine the social welfare optimum and compare it with the profit-maximizing solution, and in Section 4 we introduce the presence of a quality externality into the social welfare function. Finally, in Section 5 we offer our conclusions.

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[3] More precisely, in Crampes and Hollander [12] both the framework and the focus of analysis are different from our paper. First, in their duopoly model both firms share a common cost function, which is linear in terms of quantity and convex in terms of quality. We do not restrict the cost function to be equivalent among firms. In our case, the Crampes-Hollander assumption holds when firms are equally efficient in investment, measured in terms of the cost reduction that follows from investing. Second, Crampes and Hollander explore the implications of a minimum quality standard to social welfare and the behavior of high-quality and low-quality producers. They show, under a binding minimum quality requirement, that the high-quality producer is worse-off and the low-quality producer is better-off than in an unregulated equilibrium. Moreover, the social welfare effect of the minimum quality standard is positive if the required quality standard is “sufficiently close” to the one chosen by the low-quality producer in the unregulated equilibrium.

2 AN EXTENDED MODEL WITH PRICE, QUALITY AND INVESTMENT COMPETITION

In this section we develop and analyze a duopoly model of vertical product differentiation with endogenous investments.

2.1 Basic Model

We assume that consumers can observe the quality choices of firms and have the following utility function,

$$u = \theta s_k - p_k \tag{1}$$

where s_k and p_k are, respectively, the (environmental) quality and price of a good of quality k and the term θ represents consumer's taste parameter.[4]

There are two qualities of goods corresponding to two types of firms, k = H (high quality) and k = L (low quality). θ can be reinterpreted as each consumer's marginal willingness to pay for environmental quality, which is *uniformly* distributed on the interval $\theta \in [\underline{\theta}, \overline{\theta}]$. Each consumer purchases one unit of the good. The indifferent consumer has a threshold taste parameter $\hat{\theta} = \dfrac{p_H - p_L}{s_H - s_L}$. When the market is fully covered, the demands for high and low quality goods are defined by $d_H = \overline{\theta} - \hat{\theta}$ and $d_L = \hat{\theta} - \underline{\theta}$, respectively.[5]

Environmental quality refers here to the cleanness of production, which can be increased by abating pollution resulting from production. Abatement of pollution can entail variable and fixed costs. Variable costs reflect ongoing abatement effort by a firm, while fixed costs could be thought of as abatement technology investment.[6] (e.g., Amacher and Malik [1],

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[4] Table I provides a definition of all symbols. In what follows, derivatives will be noted by primes for functions with one argument, and partial derivatives will be denoted by subscripts for functions with many arguments.

[5] Under full market coverage, production does not change while quality may change. This allows us to focus sharply on quality competition and investments.

[6] Investment in technologies is ubiquitous among ecolabeling participants. Many ecolabeling schemes often encourage participating firms to use only the "best available technologies" to achieve required environmental quality targets (e.g., Goodland [17], OECD [27]). Some schemes in both agricultural and non-agricultural contexts tie ecolabeling specifically to technology adoption (Ashford [6], Ravenswaay and Blend [29]). A common assumption is that firms must consider either modifications to existing technologies or new technologies in order to satisfy a third party auditor. This is the case even in de facto labeling schemes, such as green electricity in the U.S. Here, with power plants, the required investments to achieve the "green" distinction are costly and require large capital outlays (e.g., see Moore [24]). This is also the case with "green" wood manufacturing programs (Tarranto and Humphries [36]). Indeed, it is not surprising that in practice most ecolabeling systems have given rise to arbitragers who provide information to companies on technologies needed to meet specific label environmental quality standards.

Amacher and Malik [2], and McKitrik [22]). With this in mind, we use the following assumption regarding the costs of production:

Assumption 1. *Let* $C^k(s_k, I_k, d_k)$ *be the total costs of output production and* $c^k(s_k, I_k, d_k)$ *the respective marginal costs with the following properties*

$$(i) \quad \frac{\partial C^k(s_k, I_k, d_k)}{\partial d_k} > 0; \qquad \frac{\partial c^k(s_k, I_k, d_k)}{\partial d_k} \geq 0$$

$$(ii) \quad \frac{\partial c^k(s_k, I_k, d_k)}{\partial s_k} > 0; \qquad \frac{\partial^2 c^k(s_k, I_k, d_k)}{\partial {s_k}^2} > 0$$

$$(iii) \quad \frac{\partial c^k(s_k, I_k, d_k)}{\partial I_k} < 0; \qquad \frac{\partial^2 c^k(s_k, I_k, d_k)}{\partial {I_k}^2} > 0,$$

where d_k is the demand by a firm of type k (= H,L), s_k is the quality choice, and I_k is investment in a technology.

According to Assumption 1 the marginal cost of producing quality is convex and is decreased by investment at a decreasing rate. We use a specific form for these costs, derived by adding the fixed cost component of investment to the quadratic form common in the vertical product differentiation literature,

$$c_k(s_k, I_k) = \frac{1}{2} b s_k^2 + \alpha_k(I_k) \quad \text{for k} = H, L, \quad \text{with } \alpha_k'(I_k) < 0 \text{ and } \alpha_k''(I_k) > 0, \quad (2)$$

The cost of quality provision features both a variable and fixed component. This is consistent with capacity investment in the Dixit - Spence sense (Spence [32], Dixit [14], and Spencer and Brander [33]).

Assuming variable linear costs of output production, the profit functions of both firms can now be written,

$$\pi^k = [p_k - c_k(s_k, I_k)] d_k, \qquad \text{for } k = H, L, \qquad (3)$$

Next we analyze our three-stage game. In the first stage, firms decide whether and how much to invest in the technology. In the second stage, firms compete by choosing the level of environmental quality for their goods. The third stage has firms competing by choosing prices for their (quality) differentiated product. This sub-game perfect equilibrium relies on commitment by each firm regarding its investment and quality choices.

2.2 Price and Quality Competition

Using backward induction, we first turn to the *third* stage, in which firms choose prices subject to their previous choices for technology investment and level of environmental quality provided for their product. It is straightforward to solve for the Bertrand optimal prices and obtain the following price difference,

$$p_H^* - p_L^* = \frac{1}{3}\left[\frac{1}{2}b(s_H^2 - s_L^2) + (\overline{\theta} + \underline{\theta})(s_H - s_L) + x\right], \tag{4}$$

where $x = \alpha_H(I_H) - \alpha_L(I_L)$.[7] This term x measures the relative efficiency of each firm, in terms of the difference in their fixed cost components of providing quality. We will refer to this as the difference in cost structures between the firms.

We can see from (4) that, in addition to conventional parameters (market size, quality difference and the cost of providing quality), the price difference depends on x, i.e. on the difference in the firms' fixed costs as determined by the investment stage. If x is negative (positive), meaning that the fixed cost component of the low quality firm is higher (lower) than that of the high quality firm, then the price difference is smaller (larger). This will be important later when we interpret the investment results.

The Nash equilibrium qualities for each firm in the *second* stage can be shown to equal,[8]

$$s_H^* = \frac{5\overline{\theta} - \underline{\theta}}{4b} + \frac{2x(I_H, I_L)}{3(\overline{\theta} - \underline{\theta})} \;;\quad s_L^* = \frac{5\underline{\theta} - \overline{\theta}}{4b} + \frac{2x(I_H, I_L)}{3(\overline{\theta} - \underline{\theta})}, \tag{5}$$

so that,

$$s_H^* - s_L^* = \frac{3(\overline{\theta} - \underline{\theta})}{2b}. \tag{6}$$

The first term of equation (5) is conventional in product differentiation results. The second term in (5) is unique to our ecolabeling/investment case; this shows that the difference in fixed costs of quality provision will affect firms' optimal level of qualities, but it does not matter for quality dispersion in the market (equation 6). Referring to (5), if the difference in fixed costs is negative (positive), indicating that the fixed cost component of the low quality firm is higher (lower) compared to the high quality firm, then the quality levels for both firms

[7] It is also straightforward to show under the assumptions made that the Bertrand equilibrium is unique and stable (Crampes and Hollander [12, Appendix B] provide a proof, which works in our case as well).

will be lower (higher). After examining the investment stage, we will discuss the quality game in more detail.

Substituting the optimal quality levels (5) into the profit functions for each firm and rearranging yields the corresponding profits of the two firms when prices and qualities have been chosen optimally,

$$\tilde{\pi}^H = \frac{1}{6b}\left(\bar{\theta}-\underline{\theta}\right)\left[\frac{3}{2}\left(\bar{\theta}-\underline{\theta}\right)-\frac{4x(I_H,I_L)b}{3\left(\bar{\theta}-\underline{\theta}\right)}\right]^2 \tag{7a}$$

$$\tilde{\pi}^L = \frac{1}{6b}\left(\bar{\theta}-\underline{\theta}\right)\left[\frac{3}{2}\left(\bar{\theta}-\underline{\theta}\right)+\frac{4x(I_H,I_L)b}{3\left(\bar{\theta}-\underline{\theta}\right)}\right]^2 \tag{7b}$$

These profits depend on market size, the marginal cost of producing quality, and on investment levels I_H and I_L via the term $x(I_H, I_L)$. Firms' profits in (7a) and (7b) are equal if x is zero, like in [12]; otherwise they will differ.

2.3 Technology Investment

Now we turn to the *first* stage, where firms determine their levels of investment. Under competitive capital markets the unit cost of investment, $\hat{v}$, is equal for both firms. The *total* unit cost of investment also includes auditing costs paid by the firm, τ, required to obtain an eco-label.[9] The total unit cost is therefore written, $v = \hat{v} + \tau$. The profit functions corresponding to the maximization problem in the first stage can now be expressed with the help of (7a) and (7b) as,

$$V^H = \tilde{\pi}^H - vI_H; \qquad V^L = \tilde{\pi}^L - vI_L. \tag{8}$$

Investment in the technology is then determined via the following first-order conditions

$$V^H_{I_H} = \left[-A + Bx\right]\alpha'_{\mathrm{H}}(I_H) - v = 0 \tag{9a}$$

$$V^L_{I_L} = \left[-A - Bx\right]\alpha'_{\mathrm{L}}(I_L) - v = 0, \tag{9b}$$

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8 It can also be shown that the resulting Nash equilibrium in qualities is unique and stable, and that product quality choices are strategic complements (see Bulow et al. [10] for a discussion of this concept in a different framework).

9 Costs of ecolabeling can be specifically linked to firms' technologies. For example, the costs of ecolabeling to a firm consist of auditing costs annual license costs. While the latter is most often defined as a percentage of the annual turnover of sales (usually with an upper limit), the former is a fixed cost closely tied with the production technology used by the firm. The auditing costs vary considerably across ecolabel systems. For instance, in the European Union the Eco-Label Award system the auditing fee is about USD 500. The Nordic Swan auditing fee is USD 2000 and with the Blue Angel it lies between about USD 178 - 2034 depending on the technology in question (OECD [27]).

where $A = \frac{2}{3}\left(\overline{\theta} - \underline{\theta}\right)$, $B = \frac{16b}{27\left(\overline{\theta} - \underline{\theta}\right)}$ and $x = \alpha_H(I_H) - \alpha_L(I_L) = a_H I_H - a_L I_L$..

We show in Appendix 1 that this equilibrium is unique and stable at the interior solutions, and that investments are strategic substitutes.

Equations (9a) and (9b) show that each firm invests to equate the marginal benefit of investment, in terms of reduced costs of providing quality, to the effective unit cost of investment *v*. The sign of x is again important, this time to the investment choices made by the duopolists. If x *is zero*, then both firms invest. If x is *negative*, then the high quality firm always has positive technology investment in equilibrium, because the term in brackets of (9a) is negative. The low quality firm invests only if the bracket term in (9b) is negative. Finally, a strictly *positive* x implies that the low quality firm invests, but we now have the possibility of a corner solution for the high quality firm's investment.

To obtain a closed form solution for investment, we further specify the $\alpha_k(I_k)$ term as follows

$$\alpha_k(I_k) = e^{a_k I_k} \tag{9c}$$

where $a_k < 0$. We approximate this part of the cost function log-linearly using $e^{a_k I_k} \approx 1 + a_k I_k$, so that $\alpha_k'(I_k) = a_k(1 + a_k I_k) < 0$ and $\alpha_k''(I_k) = a_k^2 > 0$. The log-linear approximation is commonly used in many other contexts.[10]

Using the approximation (9c) for the $\alpha_k(I_k)$ terms and abstracting from the cross and squared terms we can rewrite the first order conditions (9a) and (9b) for investments as follows

$$I_H: \quad -Aa_H(1 + a_H I_H) + Ba_H(a_H I_H - a_L I_L) - v = 0 \tag{9a'}$$

$$I_L: \quad -Aa_L(1 + a_L I_L) - Ba_L(a_H I_H - a_L I_L) - v = 0, \tag{9b'}$$

where $a_H, a_L < 0$. If the fixed cost terms are identical between firms, i.e., $x = 0$, then the optimal investments and their difference are given by

$$I_H^*\Big|_{x=0} = -\frac{1}{a_H} - \frac{v}{Aa_H^2} \; ; \; I_L^*\Big|_{x=0} = -\frac{1}{a_L} - \frac{v}{Aa_L^2} \tag{10a}$$

$$\left[I_H^* - I_L^*\right]_{x=0} = \frac{a_H - a_L}{a_H a_L}\left[1 + \frac{v(a_H + a_L)}{Aa_H a_L}\right] > (\leq) 0 \text{ as } a_H < (\geq)\, a_L, \tag{10b}$$

[10] Log-linear approximation makes the analysis more tractable and transparent; and in our case it makes it possible to provide a closed form analytical solution for the investment stage. See Campbell [11] for examples of the use of this log-linear approximation in the context of growth models and Bovenberg and van der Ploeg [9] **in** public finance contexts.

where the term in the brackets is negative.[11]

When $x \neq 0$, the optimal investments and the resulting difference in the firms' cost structure can be characterized as follows

$$I_H^*\Big|_{x\neq 0} = -\frac{1}{a_H}\left[1+\frac{v[Aa_L - B(a_H + a_L)]}{Aa_H a_L(A-2B)}\right];\ I_L^*\Big|_{x\neq 0} = -\frac{1}{a_L}\left[1+\frac{v[Aa_H - B(a_H + a_L)]}{Aa_H a_L(A-2B)}\right] \quad (10c)$$

$$x^* = \frac{v(a_H - a_L)}{a_H a_L(A-2B)} \begin{Bmatrix} < \\ > \end{Bmatrix} 0 \text{ as } a_H \begin{Bmatrix} < \\ > \end{Bmatrix} a_L, \quad (10d)$$

where $A-2B>0$ at the interior solution for the unique and stable duopoly investment game. The difference between the optimal investment levels of the firms can now be expressed as,

$$\left[I_H^* - I_L^*\right]_{x\neq 0} = \frac{a_H - a_L}{a_H a_L}\left\{1+\frac{v[(a_H + a_L)]}{Aa_H a_L}\frac{(A-B)}{(A-2B)}\right\} \quad (11)$$

where $(A-B)/(A-2B)>1$. Thus when x < 0 (equivalent to $a_H < a_L$), the difference in (11) is positive. If x > 0, an interior solution for both firms requires $a_H > a_L$, then the sign of (11) is reversed. We summarize our findings in,

Proposition 1. *At the interior solution for investments, the equilibrium is unique and stable, and investments of the firms are strategic substitutes.* ***The outcome of the investment game depends on the relative efficiency of firms' in terms of their difference in the fixed costs of providing quality, x, as follows:***

a) If $x<0$, then $I_H^*>0$ but $I_L^*=0$ is possible if the unit cost of investment is "high enough".
b) If $x=0$, then $I_H^*>0$, and $I_L^*>0$.
c) If $x>0$, then $I_L^*>0$ but $I_H^*=0$ is possible if the unit cost of investment is "high enough".

Thus, naturally the more efficient firm invests more. In the case of equal efficiency of investing, both firms invest and their fixed costs become identical (x = 0). Note also that the higher is the effective unit cost of investment (i.e., the cost of auditing for ecolabeling), the greater is the possibility of a corner solution with one firm not investing. Later we show that the resulting cost structure has crucial implications for quality competition.

In Appendix 2 we study the implications of the case where firms can influence the marginal willingness to pay of consumers by investments. Following studies of advertising in

[11] Given that the efficiency of investment in reducing fixed costs is expected to be at most about 50 percent, then $(a_H + a_L)/a_H a_L \leq -4$. Normalizing $\overline{\theta} - \underline{\theta} = 1$ in the A-term makes the negativity clear.

the industrial organization literature (Dixit and Norman [15]), we can express marginal willingness to pay as a function of investments. This assumes that investment is a product characteristic which increases utilities of consumers (Bontems and Requillart [8]). In this case, it turns out that the possibility for $I_L^* = 0$ when $x < 0$ increases, but the possibility of $I_H^* = 0$ when $x > 0$ decreases. The economic intuition goes as follows: Investment by the low quality firm would increase price competition with the high quality firm, because willingness to pay for low quality consumers would increase, and thus there would be less marginal gains from differentiating through investment. Similarly, increased willingness to pay for high quality strengthens the high quality firm's incentives to invest, even though it is less efficient in investing. Hence, when marginal willingness to pay depends on investment, this serves to reinforce the incentive for the high quality firm to obtain eco-labeling rights via technology investment.

2.4 Closing the duopoly competition: environmental quality and price competition

Using the solutions for optimal investments, we can now characterize the quality competition stage under *endogenous* investments. According to equation (10c) we have $x^* = \dfrac{v(a_H - a_L)}{a_H a_L (A - 2B)} < (\geq) 0$ as $a_H - a_L < (\geq) 0$. Substituting this expression for x in (5) we obtain the following profit maximizing qualities, written in terms of exogenous variables.

$$s_H^* = \frac{5\overline{\theta} - \underline{\theta}}{4b} + \frac{2v(a_H - a_L)}{3(\overline{\theta} - \underline{\theta})(A - 2B) a_H a_L} \qquad s_L^* = \frac{5\underline{\theta} - \overline{\theta}}{4b} + \frac{2v(a_H - a_L)}{3(\overline{\theta} - \underline{\theta})(A - 2B) a_H a_L} \qquad (5')$$

We can now distinguish several alternative outcomes for the quality game. Here we focus solely on interior solutions where both firms invest, because corner solutions with one firm not investing leads to qualitatively similar outcomes as interior solutions.[12]

We start with the benchmark case where the firms' cost structures are identical with respect to investment, x = 0 (i.e., $a_H - a_L = 0$). In this case, the last terms in (5') are zero like in the case analyzed in Crampes and Hollander [12] without investment decisions. The interpretation of their result in our model is different, however. Comparing (5') with (5) reveals immediately that, in our model, the firms provide *either* higher or lower quality than in the

[12] This is because in a corner solution with one firm not investing x must be either positive or negative. Recall that if x < 0 then $I_H > 0, I_L = 0$ and if x > 0 then $I_H = 0, I_L > 0$ in the corner solutions.

absence of investments. Specifically, if the difference between the initial fixed costs was negative (positive), then quality provision after the investment stage is higher (lower). Thus, the result in Crampes and Hollander [12] is a special case of our investment-based model with identical cost structures for firms.

At the interior solution where both firms invest, the resulting cost structure may differ, i.e., we may have either $x < 0$, or $x > 0$. If $x < 0$, so that the high quality firm is more efficient in investing, then the resulting qualities provided in the market are lower than in the benchmark case of $x = 0$. This is because, under $x < 0$, the high quality firm has lower fixed costs compared to the low quality firm. Thus, the high quality firm performs better in price competition, and it does not need to produce very high quality in order to mitigate price competition with the low quality firm. If instead $x > 0$, so that the low quality firm is more efficient in investing, then the last terms in (5') are positive and higher quality would be produced than when firms have an identical cost structure ($x = 0$). In this case, the high quality firm is less efficient; it therefore provides higher quality to mitigate price competition.[13] These findings are summarized in

Proposition 2. *The possibility that investment affects fixed costs of providing quality leaves quality dispersion unchanged, but it affects duopolists' incentives for providing (environmental) quality. The quality provided by the market is highest when the low quality firm is more efficient at investment and lowest when the high quality firm is more efficient at investment.*

The economic interpretation goes as follows. Investment changes the firms' relative profitability and thus conditions of price competition. Mitigation of price competition in turn affects the choice of qualities. This explains our finding of environmental quality being lowest (highest) when the high quality firm is more (less) efficient at investing. One may ask why the *difference* in quality among firms is equal over all cases. This is because investments affect the fixed cost but not the variable cost of quality provision. The marginal cost of quality provision remains the same in all cases and, consequently, the quality dispersion does not change.

[13] When both firms invest the duopoly equilibrium with a positive price difference exists for $x > (<)\ 0$, and the profits of the high quality firm are greater (smaller) than the profits of the low quality firm when $a_H < (>)\ a_L$. All consumers are consuming one unit of the commodity when $\underline{\theta} > \frac{p_L}{s_L}$.

3 SOCIALLY OPTIMAL QUALITY AND INVESTMENT DECISIONS

The equilibrium characterized above results from profit maximizing decisions of firms. We now examine the *first best* levels of qualities and investment as a benchmark. Note first that it is socially optimal to produce both high and low quality goods, because variable costs of producing quality are nonzero (Ecchia et al. [16] provides a proof of this and further discussion).

We consider a utilitarian social welfare function, which is the sum of consumer and producer surplus,

$$SW = (\bar{\theta} - \tilde{\theta})[\frac{\bar{\theta} + \tilde{\theta}}{2} s_H - c_H(s_H)] + (\tilde{\theta} - \underline{\theta})[\frac{\underline{\theta} + \tilde{\theta}}{2} s_L - c_L(s_L)] - v(I_H + I_L), \qquad (12)$$

In (12) both variants of quality are sold at marginal cost, so that the index of the marginal consumer indifferent between consuming high and low quality goods is modified accordingly, $\tilde{\theta} = \frac{\bar{\theta} + \underline{\theta}}{2}$. Note that the high and low quality firms split the market into two halves of equal size: $\bar{\theta} - \tilde{\theta} = \tilde{\theta} - \underline{\theta}$.

3.1 Environmental Quality Choice

We first examine differences in quality provided by the two firms under the social welfare maximizing case, and then compare this with the profit maximizing case. First, we differentiate (12) with respect to s_H and s_L and solve for socially optimal qualities, obtaining $s_H^W = \frac{3\bar{\theta} + \underline{\theta}}{4b}$ and $s_L^W = \frac{\bar{\theta} + 3\underline{\theta}}{4b}$, where the superscript 'W' denotes the social welfare optimum, so that $s_H^W - s_L^W = \frac{\bar{\theta} - \underline{\theta}}{2b}$. Due to the absence of strategic interaction of firms in the social optimum, these quality choices are independent of each other and of investments in the (green) technology. Consequently, the socially optimal qualities and quality difference under the social welfare optimum are both different from the ones obtained under profit maximization.

The following relationship holds comparing the social welfare maximizing qualities with profit maximizing ones (obtained from (5)),

$$s_H^* - s_H^W = \left[\frac{\bar{\theta} - \underline{\theta}}{2b}\right] + \frac{2v(a_H - a_L)}{3(\bar{\theta} - \underline{\theta})(A - 2B)a_H a_L} \qquad (13a)$$

$$s_L^* - s_L^W = -\left[\frac{\overline{\theta} - \underline{\theta}}{2b}\right] + \frac{2v(a_H - a_L)}{3(\overline{\theta} - \underline{\theta})(A - 2B)a_H a_L} \tag{13b}$$

where '*' continues to denote each firm's profit maximizing choices. The quality difference depends on two terms, on the spread of consumer tastes, and on the firms' relative efficiency in investment $(a_H - a_L)$. The spread term is positive for the high quality firm and negative for low quality firm by definition. If the low quality firm is more efficient in investing $((a_H - a_L) > 0)$ so that quality competition is more intense, then the latter terms are positive. The high quality firm overprovides quality, but the low quality firm's behavior is ambiguous. If the high quality firm is more efficient in investing $((a_H - a_L) < 0)$, so that quality competition relaxes, then (13a) is ambiguous while (13b) is negative. Now, the low quality firm *underprovides*. It may therefore be possible that both firms underprovide qualities. Finally, when $(a_H - a_L) = 0$, we have the special case of Crampes and Hollander [12]. Here, the spread of quality among firms in the profit maximizing duopoly is too large compared to the social optimum.

In sum, profit maximization leads to incentives for the firms to increase quality differences among them in order to relax price competition. The severity of price competition depends on the firms' relative efficiency of investing in the green technology, and on the resulting cost structure. Therefore, while the social welfare optimum features marginal cost pricing, the market provision of qualities may be lower or higher depending on how investments affect the relative cost structure of firms.

3.2 Technology Investment Choice

Next we consider the socially optimal level of technology investment, where investment can affect the fixed costs of providing quality. From the necessary conditions for an interior solution we have,

$$I_H^W = -\frac{1}{a_H} - \frac{v}{\frac{1}{2}(\overline{\theta} - \underline{\theta})a_H^2} \tag{14a}$$

$$I_L^W = -\frac{1}{a_L} - \frac{v}{\frac{1}{2}(\overline{\theta} - \underline{\theta})a_L^2} \quad , \tag{14b}$$

In (14a-b), the first RHS terms dominate. Like in the case of quality provision, high and low quality investments are independent of each other, because socially optimal investment is not determined as a result of firms' interaction in the investment game. The difference between the socially optimal high and low quality firm investments is given by

$$I_H^W - I_L^W = \frac{a_H - a_L}{a_H a_L}\left[1 + \frac{v(a_H + a_L)}{\frac{1}{2}(\bar{\theta} - \underline{\theta})a_H a_L}\right], \tag{14c}$$

where we assume that the braced term is negative, i.e., the last term is greater than one in absolute value. The sign of the first term before the brackets depends on firms' relative efficiency in investing. Thus, the whole expression is positive (negative) if the high quality firm is more (less) efficient in investing.

Now consider how the socially optimal investment levels relate to the profit maximizing duopoly investment levels. Using (14a), (14b), (10a) - (10b) for the case x = 0 yields

$$I_H^* - I_H^W = \frac{v}{3a_H^2 A} > 0 \tag{15a}$$

$$I_L^* - I_L^W = \frac{v}{3a_L^2 A} > 0 \tag{15b}$$

Thus, from the society's viewpoint both firms invest too much, because they use investing in the green technology as a means of mitigating price competition**.** For the case $x \neq 0$ we obtain from (14a), (14b) and (10c), (10d),

$$I_H^* - I_H^W = \frac{v}{Aa_H^2}\left\{\frac{(a_H + a_L)B - Aa_L}{Aa_L(A - 2B)} + \frac{4}{3}\right\} \tag{15c}$$

$$I_L^* - I_L^W = \frac{v}{Aa_L^2}\left\{\frac{(a_H + a_L)B - Aa_H}{Aa_H(A - 2B)} + \frac{4}{3}\right\}. \tag{15d}$$

The signs of the first terms in braces of (15c) and (15d) are ambiguous, but there is clearly a possibility of over-investing. The sufficient (but not necessary) condition for the high quality firm to over-invest is that $(a_H + a_L)B < Aa_L$, and for the low quality firm that $(a_H + a_L)B < Aa_H$. We summarize our findings in

Proposition 3. *The relationships between the socially optimal and profit-maximizing investment levels are the following*

- *a)* $I_H^W - I_L^W \geq (<)\, 0$, *if* $a_H \leq (>)\, a_L$ *i.e. the socially optimal investment levels depend on the efficiency of investments*
- *b)* $I_H^* - I_H^W > 0$ and $I_L^* - I_L^W > 0$ for $x = 0$, *i.e. profit maximizing firms that are equally efficient invest too much*
- *c)* $I_H^* - I_H^W > 0$ and $I_L^* - I_L^W > 0$ likely for $x \neq 0$, *i.e. profit maximizing firms under unequal efficiency will likely invest too much.*

The intuition for Proposition 3 mirrors our earlier discussions regarding the relative difference in fixed costs of investment between firms. In the duopoly outcome, firms invest to decrease costs and relax price competition. The social welfare maximizer perceives no rents from relaxing price competition due to marginal cost pricing. Thus, we would generally expect the social welfare maximizer to invest less. Finally, we can show allowing for endogenous marginal willingness to pay increases investment for the high quality firm relative to the profit maximizing outcome, but its effect on the low quality firm remains ambiguous (see Appendix 2 for further details).

According to Proposition 3, there is a tendency for excessive investment by profit maximizing firms. The government can decrease this excess and increase the provision of environmental quality by introducing ecolabeling only under certain conditions. Suppose that obtaining an ecolabel is linked to an auditing or application procedure, made by an independent government agency, which ensures that the firm has really installed a green technology. Then, charging firms a reasonable fee for auditing will always decrease excessive investments. Ecolabeling increases environmental quality if it tightens quality competition between the firms. Given our previous analysis, we know this can happen when the duoply shifts from more relaxed to tighter quality competition, i.e., when the cost difference shifts from $x < 0$ to either $x = 0$ or $x > 0$ with investment. We can characterize this finding as

Proposition 4. *If ecolabeling involves costs that raise firms' effective unit cost of investment, then it decreases excessive investments in green technologies and increases environmental quality when the market under-provides it. If the marginal willingness to pay for high quality goods is affected by the ecolabel (investment), then the possibility of only the high quality firm obtaining an ecolabel is higher.*

Interestingly, this result holds even though we have not assumed the presence of environmental externalities from inefficient average quality provided by the market.

4 EXTERNALITIES AND SOCIAL WELFARE

Thus far we have established that the profit maximizing cases can involve different levels of quality. We now consider the presence of an explicit externality related to average environmental quality provided in the market.[14] The interpretation is that consumer utility is increasing in average quality. Like Cremer and Thisse we assume that the utility of each consumer is now written,

$$u^e = \theta s_k - p_k + \gamma\theta s_a \tag{16}$$

where the superscript 'e' denotes the presence of a positive externality, and 's_a'denotes average market product quality. Average quality is defined by weighting the quality of both firms by their demands; given that market shares are equal, this weighted average quality is $s_a = (s_H + s_L)/2$. Notice that, because a single consumer cannot affect average quality by their actions, the externality term will be a constant in any consumer's optimization problem. It will not be a constant, though, when the social optimum is determined.[15]

Using (16), the social welfare function in (12) is now modified as follows,

$$SW^e = SW + \gamma(\overline{\theta} - \underline{\theta})[\frac{\overline{\theta} + \underline{\theta}}{2} s_a] = SW + \frac{\gamma(1+\gamma)}{2b}[(\overline{\theta} - \underline{\theta})(\overline{\theta} + \underline{\theta})^2], \tag{17}$$

4.1 Environmental Quality Choice

Turning first to the determination of qualities, we differentiate (17) with respect to high and low quality levels, for a given investment, and find,

$$SW^e_{s_H} = \frac{3\overline{\theta} + \underline{\theta}}{4} - bs_H + \gamma\frac{(\overline{\theta} + \underline{\theta})}{2} = 0 \tag{18a}$$

$$SW^e_{s_L} = \frac{3\underline{\theta} + \overline{\theta}}{4} - bs_L + \gamma\frac{(\overline{\theta} + \underline{\theta})}{2} = 0 \tag{18b}$$

Solving these for the socially optimal qualities in the presence of the externality, we find

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[14] Cremer and Thisse [13] provide an analysis of the potential role of externalities in a different product differentiation context.

[15] We could alternatively express consumer utility (equation 16) as follows: $u^e = \theta_k s_k - p_k - \gamma E$, where $E = (\overline{s} - s_H)d_H + (\overline{s} - s_L)d_L$ and $\overline{s}$ denotes unabated emissions. Given that $d_H + d_L = (1/2) + (1/2) = 1$ we can express the utility function as $u^e = \theta_k s_k - p_k - \gamma(\overline{s} - s_a)$. Hence this formulation will lead to the same results.

$$s_H^{we} = \frac{3\overline{\theta} + \underline{\theta} + 2\gamma(\overline{\theta} + \underline{\theta})}{4b}\,;\; s_L^{we} = \frac{3\underline{\theta} + \overline{\theta} + 2\gamma(\overline{\theta} + \underline{\theta})}{4b}\,;\; s_H^{we} - s_L^{we} = \frac{3\overline{\theta} + \underline{\theta}}{4b} \qquad (19)$$

Hence, again, qualities are not affected by the investments. Accounting for the externality increases both firms' qualities by an equal amount because the externality is symmetric.

More intuition can be gained by comparing optimal qualities across the various social welfare and profit maximizing equilibria. We are specifically interested in finding cases where there is *underprovision* of quality in the profit maximizing equilibrium relative to the social welfare optimum. Using (13a), (13b) and (19) we can see that the socially optimal qualities are always higher in the presence of externality:

$$s_H^{we} - s_H^{w} = s_L^{we} - s_L^{w} = \frac{\gamma(\overline{\theta} + \underline{\theta})}{2b} \equiv \Omega \quad > 0 \qquad (20a)$$

While this is intuitive, it is more interesting to ask how the market solution relates to socially optimal provision of environmental quality. When both firms are equally efficient in investment, equations (5') and (19) imply that:

$$(s_H^{we} - s_H^{*})\big|_{a_H = a_L} = -\frac{\overline{\theta} - \underline{\theta}}{2b} + \frac{\gamma(\overline{\theta} + \underline{\theta})}{2b} \equiv \Phi\,;\; (s_L^{we} - s_L^{*})\big|_{a_H = a_L} = \frac{\overline{\theta} - \underline{\theta}}{2b} + \frac{\gamma(\overline{\theta} + \underline{\theta})}{2b} \equiv \Psi > 0 \qquad (20b)$$

Hence, the quality difference depends on the taste spread term and on the size of the externality. The low quality firm underprovides quality, while the high quality firm may or may not under-provide. If the relative efficiency in investment differs we can show that this is important to the spread in quality,

$$(s_H^{we} - s_H^{*})\big|_{a_H \neq a_L} = \Phi - \frac{2v(a_H - a_L)}{3(\overline{\theta} - \underline{\theta})(A - 2B)a_H a_L}\,;\; (s_L^{we} - s_L^{*})\big|_{a_H = a_L} = \Psi - \frac{2v(a_H - a_L)}{3(\overline{\theta} - \underline{\theta})(A - 2B)a_H a_L} \qquad (20c)$$

Now, understandably, the quality difference depends on both the size of the externality and the relative efficiency of firms' investments in the green technology. When $(a_H - a_L) < 0$ so that high quality firm is more efficient in investment and quality competition is less severe, both firms underprovide environmental quality according to (20c). However in the reverse case, when $(a_H - a_L) > 0$, which leads to more intensive quality competition, overprovision of quality may be possible. We present our main findings as

Corollary 3. *In the presence of environmental externalities, the possibility of overprovision of environmental quality by a duopoly decreases and that of underprovision increases.*

The possibility of underprovision of environmental quality by a high quality firm is an important departure from the two-stage quality competition literature. When firms are identical, the possibility of under-provision in our model depends on the size of the externality. If, in addition, the high quality firm is more efficient in investment, then this serves to relax quality competition and thus reinforces the effect of any externality. Thus, given duopolists' investment behavior, the needs of price competition determine how much the high quality firm underprovides.

4.2 Technology Investment Choice

We finally comment on socially optimal technology investments in the presence of a positive average quality externality. The necessary conditions for investment under an externality are identical to the case of no externality (see equations 14a and 14b). Thus, investments for quality provision are based on differences across firms in the efficiency of investment. Intuitively, quality choices are used to mitigate externalities, and investments are the means for a firm to achieve efficient quality cost reductions. If marginal willingness to pay depends on investment, then the presence of an externality increases investment for the high quality firm, but investment for the low quality firm remains ambiguous.

Thus our previous comparison of private and socially optimal investment levels continues to hold. How does the externality affect the role of ecolabeling in environmental policy? As equations (20b) and (20c) demonstrate, the number of cases where the market underprovides quality is increased by the presence of an externality. Thus, again, ecolabeling might be used to achieve the dual goals of decreasing excessive investment and increasing environmental quality in the market (thereby mitigating externalities).

5 CONCLUSIONS

In most market settings, considerable emphasis has been placed on understanding investments firms make in 'clean' technologies that can reduce pollution associated with production. At the same time there have been numerous empirical examples of firms obtaining the right to eco-label their goods. In its purest sense, ecolabeling provides firms with a means of differentiating products. Ecolabeling often induces or effectively requires firms to adopt green technologies, because these reduce the costs of providing high levels of environmental quality required to obtain or continue holding ecolabeling rights. Thus, to understand incentives for firms to achieve high environmental quality of their production processes and receive eco-labels, and to identify the socially optimal level of environmental quality in markets where goods are not homogenous in quality, we must first understand how firms make investment choices when products can be differentiated.

We therefore extend vertical product differentiation literature to incorporate a firm's choice of technology investment, which is made prior to environmental quality and price competition decisions. A Nash game is solved over three stages: in the first stage, each firm chooses the level of their technology investment, in the second stage firms choose their environmental quality levels conditional on this investment, and the third stage has the firms competing in product markets. The resulting duopoly solution is then compared to the socially first best solution, in cases where externalities are absent or present, and where consumer willingness to pay does and does not depend on firms' investments in technologies.

We showed firms' incentives to invest in technologies that can be used to provide increased environmental quality at lower costs, and can allow the firm to obtain and retain eco-labels, depend critically on differences in their cost structures. If firms are identical with respect to fixed costs, then both firms will always invest in green technologies. If the high quality firm is more effective at investing, then the low quality firm may or may not invest depending on the unit cost of investment. The opposite holds if the low quality firm is more efficient in investing. We have also shown that market-driven incentives for high quality firms to invest are reinforced if technology investment increases consumer marginal willingness to pay for environmental quality; but this is not true for a low quality firm.

One of our most important findings is that the incentives to invest and the possibilities of corner solutions in investment differ depending on the efficiency of investment across firms. The differences in incentives to invest lead to strikingly different outcomes for the provision of environmental quality in a market. Surprisingly, quality competition will be highest among firms when the low quality firm is more efficient in investing. Quality competition is lowest when the high quality firm is more efficient in investing. Between these cases, i.e., when the firms are equally efficient in investment, we arrive at the basic results of quality competition characterized by Crampes and Hollander [12]. Our model therefore generalizes the vertical differentiation literature.

We have also compared the duopoly outcome with the socially optimal one. According to our results the possibility of a corner solution in investment never occurs at the social optimum. In the absence of environmental externalities, the quality dispersion and average quality chosen under the profit maximizing firms again depends on their relative efficiency in investment. If the high quality firm in more efficient in investing, then both firms usually underprovide quality. Interestingly, the presence of environmental externalities increases the possibility of underprovision in cases where the firms have identical cost structures, or where the low quality firm is more efficient in investing.

Our analysis has important implications for a government targeting the ecolabeling behavior of firms. Ecolabeling, by changing the firms' effective unit cost of investment, might be used to achieve the dual goal of reducing excessive investments and increasing average environmental quality, both in the absence and presence of externalities related to low average environmental quality. For example, a government interested in achieving a desired environmental quality target in markets where ecolabeling exists can use ecolabeling criteria and auditing/license charges as a means of decreasing the types of excessive investments we show could exist. However, the ability of the government to do this depends on the difference in cost structure between the firms, i.e., which firm is more efficient in terms of the effects of investment on its costs.

It is worth noting that we have conducted our analysis assuming consumers can observe the investment levels of firms, and firms can observe the preferences of consumers. An interesting area for further research would be to allow for asymmetric information between firms and consumers regarding environmental qualities of firms' products. This would require modeling of eco-labeling as a signal for consumers. While going beyond the scope of our paper, this remains an important area for further research.

Table I. Notation used in the paper

$k = H,L$	Index of technology for high quality (H) and low quality (L) cost firms
b	Marginal cost parameter for provision of quality by firm $k = H,L$
$\alpha_k(I_k)$	Fixed costs of quality provision depending on investment.
s_k	Quality of goods provided in second stage
$c_k(s_k,I_k)$	Total cost of providing quality for the firm $k = H,L$
p^*_k	Optimal (Bertrand) prices from third stage price competition for high and low quality goods
u	Utility of consumer i
π^k	Profit function for low quality ($k = L$) and high quality ($k = H$) firms
s_k^*	Quality level of goods provided by duopoly for low ($k = L$) and high ($k = H$) quality
s_k^w	Socially optimal quality level of goods for low ($k = L$) and high ($k = H$) quality
s_k^{we}	Quality level of goods provided in market under the externality case for low ($k = L$) and high ($k = H$) quality
x	Difference in fixed costs, $x = x(I_H,,I_L) = \alpha_H(I_H)-\alpha_L(I_L)$
θ	Consumer i's taste parameter, i.e., marginal willingness to pay for good
$\hat{\theta}$	Threshold taste parameter for consumer who is indifferent between consumption of high and low environmental quality goods
$\bar{\theta}$	Upper bound on consumers' marginal willingness to pay for environmental quality
$\underline{\theta}$	Lower bound on consumers' marginal willingness to pay for environmental quality
$\tilde{\theta}$	Index of marginal consumer when both high and low quality goods are sold at marginal cost
I^k	First stage investment in technology for firm $k = H,L$.
I_{Wk}	Social welfare maximizing level of investment in technology ($k = H,L$)
d_k	Demand (number of consumers) purchasing high ($k = H$) and low ($k = L$) quality goods
$\tilde{\pi}^k$	Profits of high and low quality firms ($k = (H,L)$), gross of investment costs, when prices and qualities have been chosen optimally
V^k	Profit function corresponding to first stage, where firms choose their production technology
u^e	Utility of consumer i in the presence of an externality
γ	Weight reflecting the magnitude of the externality
s_a	Average level of environmental quality across the firms
SW	Social welfare function in the absence of environmental-quality related externalities

$\overline{\theta}_k$	Partial derivative of upper bound on marginal willingness to pay wrt quality k = H,L
$\underline{\theta}_k$	Partial derivative of lower bound on marginal willingness to pay wrt quality k = H,L
v	Unit cost of investment
SW^e	Social welfare function in the presence of environmental-quality related externalities

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Appendix 1. Proof of a Stable Nash Equilibrium, and of Investments as Strategic Substitutes, When Willingness to Pay is Independent of Investment

Re-express the first-order conditions for the investment game as follows:

$$V_{I_H} = (y-z)\alpha'_H - v = 0 \qquad \text{A1.1}$$

$$V_{I_L} = (y+z)\alpha'_L - v = 0\,, \qquad \text{A1.2}$$

with $y = \frac{2}{3}(\bar{\theta} - \underline{\theta}) > 0$ and $z = \frac{16bx}{27(\bar{\theta} - \underline{\theta})} < 0$.

The second-order conditions and the cross-derivatives are

$$V_{I_H I_H} = (y-z)\alpha''_H - \alpha'^2_H \frac{z}{x} < 0 \qquad \text{A1.3}$$

$$V_{I_L I_L} = (y+z)\alpha''_L{}' - \alpha'_L{}^2 \frac{z}{x} < 0\,, \qquad \text{A1.4}$$

$$V_{I_H I_L} = V_{I_L I_H} = \alpha'_H \alpha'_L \frac{z}{x} < 0 \qquad \text{A1.5}$$

Equation (A1.5) indicates that the firm's investments in technology are strategic substitutes.

Stability and uniqueness of the investment game requires that the condition $\Delta = \tilde{V}^H_{I_H I_H} \tilde{V}^L_{I_L I_L} - \tilde{V}^H_{I_H I_L} \tilde{V}^L_{I_L I_H} > 0$ holds for the optimum. Applying equations (A1.3) – (A1.5) to this condition yields after some manipulation:

$$\Delta = (y+z)(y-z)\alpha''_H \alpha''_L - \frac{z}{x}\left[(y-z)\alpha''_L \alpha'_H{}^2 + (y+z)\alpha''_H \alpha'_L{}^2\right] \qquad \text{A1.6}$$

By rearranging we get

$$\Delta = (y+z)(y-z)\alpha''_H \alpha''_L \left\{1 - \frac{z}{x}\left[\frac{\alpha'^2_H}{\alpha''_H} + \frac{\alpha'^2_L}{\alpha''_L}\right]\right\} > 0$$

This gives as the sufficient condition for a unique and stable equilibrium, i.e., for $\Delta > 0$:

$$\frac{z}{x}\left[\frac{\alpha'_H{}^2}{\alpha''_H(y+z)} + \frac{\alpha'_L{}^2}{\alpha''_L(y-z)}\right] < 1. \qquad \text{A1.7}$$

due to the first-order conditions A1.1 and A1.2.

Appendix 2. Analysis of the Case When Willingness to Pay Depends on Investment

Denote the marginal willingness to pay for consumers of high and low quality goods $\bar{\theta}(I_H, I_L)$ and $\underline{\theta}(I_H, I_L)$, respectively.

Assumption. *Marginal willingness to pay is affected by investment according to the following derivatives:* $\bar{\theta}_H > 0$, $\bar{\theta}_L = 0$, $\underline{\theta}_L > 0$, $\underline{\theta}_H = 0$; $\bar{\theta}_H = \underline{\theta}_L$.

Thus, investment by the high quality firm affects the upper limit of marginal willingness to pay, while investment by the low quality firm affects the lower limit. This assumption relies on the fact that the demand for each firm's product is satisfied by a separate group of consumers, following Anderson et al. [3, pp. 69-70].

A. Duopoly solution

The first-order conditions for optimal investments corresponding to (9a) and (9b) are

$$V_{I_H}^H = \underbrace{V_{I_H}^H\Big|_{\bar{\theta}_H=0}}_{-} + \underbrace{\tilde{\pi}_{\bar{\theta}}^H \bar{\theta}_H}_{+} = 0 \qquad \text{A2.1}$$

$$V_{I_L}^L = \underbrace{V_{I_L}^L\Big|_{\underline{\theta}_L=0}}_{+} + \underbrace{\tilde{\pi}_{\underline{\theta}}^L \underline{\theta}_L}_{-} = 0, \qquad \text{A2.2}$$

where $\frac{\partial \tilde{\pi}^H}{\partial \bar{\theta}} = \frac{27(\bar{\theta}-\underline{\theta})^2}{24b} - \frac{2x}{3}\left[1 + \frac{4xb}{9(\bar{\theta}-\underline{\theta})^2}\right] > 0$ as $9(\bar{\theta}-\underline{\theta})^2 + 4xb \geq 0$ - which is consistent with the condition for the incentive of low quality firm to invest $9(\bar{\theta}-\underline{\theta})^2 + 8xb < 0$ - and $\frac{\partial \tilde{\pi}^L}{\partial \underline{\theta}} = -\left[\frac{27(\bar{\theta}-\underline{\theta})^2}{24b} + 2x + \frac{8xb}{9(\bar{\theta}-\underline{\theta})^2}\right] < 0$ when $\tilde{\pi}^L > 0$. The first terms on the RHS of A2.1 and A2.2 correspond to the RHS terms of (9a) and (9b). The second RHS terms in A2.1 and A2.2 indicate how changes in willingness to pay from investment affect the profits of firms. They imply that incentives for the high quality firm to invest increase, but incentives for the low quality firm decrease when the willingness to pay depends on investments.

The second-order conditions and the cross-derivatives are

$$\frac{\partial^2 V^H}{\partial I_H^2} = \frac{\partial^2 V^H}{\partial I_H^2}\Bigg|_{\bar{\theta}_H=0} + \left[\frac{\partial^2 \tilde{\pi}^H}{\partial \bar{\theta}^2}\bar{\theta}_H + \frac{\partial \tilde{\pi}^H}{\partial \bar{\theta}}\bar{\theta}_{HH}\right] < 0 \qquad \text{A2.3}$$

$$\frac{\partial^2 V^L}{\partial I_L^2} = \frac{\partial^2 V^L}{\partial I_L^2}\Bigg|_{\underline{\theta}_L=0} + \left[\frac{\partial^2 \tilde{\pi}^L}{\partial \underline{\theta}^2}\underline{\theta}_L + \frac{\partial \tilde{\pi}^L}{\partial \underline{\theta}}\underline{\theta}_{LL}\right] < 0, \qquad \text{A2.4}$$

$$\frac{\partial^2 V^H}{\partial I_H \partial I_L} = \frac{\partial^2 V^L}{\partial I_L \partial I_H} = \frac{\partial^2 V^H}{\partial I_H \partial L_L}\Bigg|_{\bar{\theta}_H=0} + \underline{\theta}_L \tilde{\pi}_{\bar{\theta}\underline{\theta}}^L \bar{\theta}_H < 0 \qquad \text{A2.5}$$

where $\tilde{\pi}^{L}_{\underline{\theta}\bar{\theta}} = \tilde{\pi}^{H}_{\bar{\theta}\underline{\theta}} < 0$. The negativity of (A2.5) results directly from our assumptions and it shows that the dependence of the marginal willingness to pay reinforces the strategic substitutability of investments. The stability condition is given by

$$\Delta = \frac{\partial^2 V}{\partial I_H^2}\frac{\partial^2 V}{\partial I_L^2} - \left(\frac{\partial^2 V}{\partial I_H \partial I_L}\right)^2 > 0 \qquad \text{A2.6}$$

The proof of this follows the previous procedure presented in Appendix 1.

B. Social Optimum without Externalities

The social welfare maximization problem under endogenous marginal willingness to pay to yields

$$SW^{\theta}_{I_H} = \bar{\theta}_H \left[\left(\frac{SW}{\bar{\theta}-\underline{\theta}} + v(I_H + I_L)\right) + \frac{\bar{\theta}-\underline{\theta}}{2}\left(\frac{3}{4}s_H + \frac{1}{4}s_L\right)\right] - \frac{(\bar{\theta}-\underline{\theta})}{2}\alpha'_H - v = 0 \qquad \text{A2.7}$$

$$SW^{\theta}_{I_L} = \underline{\theta}_L \left[\left(-\frac{SW}{\bar{\theta}-\underline{\theta}} + v(I_H + I_L)\right) + \frac{\bar{\theta}-\underline{\theta}}{2}\left(\frac{1}{4}s_H + \frac{3}{4}s_L\right)\right] - \frac{(\bar{\theta}-\underline{\theta})}{2}\alpha'_L - v = 0\,, \qquad \text{A2.8}$$

where SW is defined in (12), and we employ an additional (common) assumption that $\underline{\theta} > bs_H$.[16] The socially optimal level of the high quality firm's investment will increase (compare A2.3 and (14a), and note that $SW^{\theta}_{I_H} > SW_{I_H}$). For the low quality firm, the effect is ambiguous (the first term in brackets of A2.4 is negative and the second term is positive). In fact, a corner solution may again exist where it is not socially optimal for the low quality firm to invest at all. However, comparing A2.3 with A2.4 suggests that the high quality firm always invests more than the low quality firm at the social optimum.

C. Social Optimum with Externalities

The necessary conditions for socially optimal investments are

$$SW^{e\theta}_{I_H} = SW^{\theta}_{I_H} + \frac{\gamma(1+\gamma)}{2b}\bar{\theta}_H(\bar{\theta}+\underline{\theta})(3\bar{\theta}-\underline{\theta}) = 0 \qquad \text{A2.9}$$

$$SW^{e\theta}_{I_L} = SW^{\theta}_{I_L} + \frac{\gamma(1+\gamma)}{2b}\underline{\theta}_L\{(\bar{\theta}+\underline{\theta})(\bar{\theta}-3\underline{\theta})\} = 0\,, \qquad \text{A2.10}$$

where the first RHS terms are given in A2.3 with A2.4. The second RHS term in A2.9 is positive, while the second term in A2.10 is ambiguous. Hence, the presence of an externality increases investment for the high quality firm, but investment for the low quality firm remains ambiguous.

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[16] This means the marginal willingness to pay of a consumer with the least intensive preference for quality exceeds the increment in marginal cost of achieving the highest quality level See, for example, Cremer and Thisse [13, Assumption 4, p.580].

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