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Environmental certification in a differentiated duopoly

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ABSTRACT
The articleaims to explore the role of horizontal product differentiation in promoting/hindering firm's participation in environmental certification. To this purpose, we consider a differentiated duopoly model where firms compete in both prices and environmental qualities. The result shows that when the level of horizontal differentiation relative to the degree of vertical differentiation is sufficiently high, only the symmetric equilibrium where both firms choose to or both choose not to certify their products exists. Asymmetric equilibrium (vertical dominance equilibrium) occurs when the level of horizontal differentiation relative to the degree of vertical differentiation is sufficiently low.

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1. Introduction

In recent years, consumers are getting more environmentally conscious. According to a G.f.K. study on environmental values and ethical shopping in 2015, globally over three quarters (76%) agree that brands and companies need to be environmentally responsible. With the increase of environmental awareness, consumers are making more environmentally conscious purchase decisions. Nielsen reveals that almost two-thirds (66%) of consumers are willing to pay extra for products and services that come from companies who are committed to positive social and environmental impact.

Although consumers prefer more environment friendly goods, they are unable to ascertain the environmental attributes of the products either on inspection or even after consumption. Such goods whose quality is not verifiable neither before purchase (*ex ante*) nor after purchase (*ex post*) without occurring high cost are called credence goods (Darby & Karni, 1973). In markets for credence goods, adverse selection occurs and can lead to market breakdown (Akerlof, 1970). A large volume of literature has developed on the functioning of the markets for credence goods and services, e.g.,Dulleck and Kerschbamer (2006); Emons (1997, 2001); Wolinsky,(1993, 1995); Zago and Pick (2004); Baksi and Bose (2007); Roe and Sheldon (2007). One possible

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solution to this problem is certification, which acts to transform unobservable credence attributes into observable search attributes.

Environmental certification has been commonly treated as one means of product differentiation available to firms in academic research. Amacher et al. (2004) model eco-labelling as green technology investment in a three-stage game with quality and price competition, and they found that firms' incentives to invest in environmental friendly technologies depend on their relative cost structure. Conrad (2005) adopts a spatial duopoly model to explore how the equilibrium prices and market shares are influenced by consumers environmental awareness and by the higher costs for producing green products. André et al. (2009) examine the Porter hypothesis within the context of a quality competition framework by using a vertically differentiated duopoly model with Bertrand competition. They suggest that a win–win situation can arise even when the switch to green goods causes an increase in production costs. Lambertini and Tampieri (2012) extend the work ofAndré et al. (2009) by considering Cournot competition between firms at the market stage. Clemenz (2010) distinguishes between two types of abatement methods: the end-of-pipe technology and the clean production technology. The author shows that the abatement technology makes a difference with respect to effectiveness and efficiency of eco-labels. Mason (2011) models certification as a noisy test, and provides the conditions for the existence of separating, pooling and partial pooling equilibria. He suggests that the introduction of an eco-label can either increase or decrease welfare. Bottega and de Freitas (2009) examine the performance of environmental certification by either a non-profit N.G.O. and a for-profit private certifier, and to compare it against the performance of a minimum quality standard (M.Q.S.). Bonroy and Constantatos (2015) provide an excellent review of the theoretical literature on labels. Li and van't Veld (2015) explore the implications of both eco-label gradation and competition. Brécard (2017) suggests that consumer misperception of competing eco-labels can weaken the firm that provides the greenest product and induce firms to use a greenwashing strategy. Baksi et al. (2017) suggest that consumers' misinformation about the quality of intermediate-quality products can influence firms' incentives to enhance product quality. Michalski et al. (2018) develop a model to find the optimal level of debt for non-profit organisation environmental conditions. Bem et al. (2019) find that in the case of Polish hospitals there is no difference in financial condition between rural and urban hospitals. Dziuba et al. (2019) examine the use of the Internet by older adults in Poland and their result suggests that older adults are becoming more digital. Polak et al. (2018) provide a future roadmap for treasury management. Poret (2019) consider a model in which two types of N.G.O.s (quality-driven N.G.O.s and market-driven N.G.O.s) compete to offer firms labels and find that their competition results in a decrease in standards set by the quality-driven N.G.O., while an increase in standards offered by the market-driven N.G.O. Pal and Saha (2015) examine the environmental impact of optimal privatisationand pollution tax in a mixed duopoly with differentiated products. Xing et al. (2019) explores the optimal environmental R&D subsidy in a mixed duopoly with spill-overs. Hirose et al. (2017) incorporate environmental corporate social responsibility into sequential price competition and show that the first-mover has the advantage. Liu et al. (2015) analyse the firms' incentives for adopting strategic environmental corporate social responsibility and the N.G.O. certifier's rationale on standard setting.

Closer in spirit to our articleisDas (2016). Das (2016) considers a horizontally differentiated duopoly model and studies how the level of horizontal product differentiation and the objective function of a certifier (for-profit or non-profit) affect the equilibrium of the market. He suggests that under a non-profit certifier which certifies the highest quality products only, it is always the case that both firms produce the highest quality and opt for certification. Under a for-profit certifier, he shows that when the variants are not sufficiently horizontally differentiated, only one firm opts for the certification whereas the other supplies the lowest quality. InDas (2016) the horizontal dimension is modelled by Hotelling line while consumers' willingness to pay (W.T.P.) for environmental quality is assumed to be homogeneous. In this article, followingNeven and Thisse (1990), we propose a model combining both horizontal and vertical differentiation to account for two-dimensional competition. Using this framework, we have studied the impacts of horizontal differentiation on firms' incentives for adopting environmental certification. The results show that when the level of horizontal differentiation relative to the degree of vertical differentiation is sufficiently high, there exists only the symmetric equilibrium where both firms choose to or both choose not to certify their products. Asymmetric equilibrium where a single firm opts for the certification occurs when the level of horizontal differentiation relative to the degree of vertical differentiation is sufficiently low.

The remainder of this articleis organisedas follows. Section 2 is devoted to the formulation of the model. In Section 3 we consider consumers purchase decision at the final stage. In Section 4, we study the price competition at the third stage. In Section 5, we examine the certification decisions whether the two firms choose to certify or not at the second stage. We summariseour main conclusions in Section 6. All proofs are given in an appendix.

2. The model

We consider a market with two competing firms, indexed by i, $i=1,2$. Each firm sells a horizontally differentiated product. To model horizontal differentiation, we assume that the two firms/products are located at the extreme locations of the Hotelling line. Letting l_i denote firm/product i's 'location' on the horizontal dimension. Without loss of generality we assume that firm/product 1 is located at the extreme left ($l_1 = 0$), and firm/product 2 is located at the extreme right ($l_2 = 1$). In this model, the horizontal differentiation between the two firms is exogenous. The two firms can endogenously determine the environmental qualities of their products. *Ceteris paribus*, we assume that all consumers prefer the product with higher environmental quality, which means that environmental quality is a vertical differentiation attribute in our model.

The mass of consumers is normalisedto one. Each consumer is characterisedby his/her 'most preferred' location (denoted by x) on the horizontal dimension and by his/her W.T.P. on environmental quality (denoted by θ). These two characteristics x and θ are assumed to be independently and uniformly distributed on $[0, 1] \times [0, 2\overline{\theta}]$, where $\overline{\theta}$ represents the average WT.P. for environmental quality among consumers. Letting qi denote the environmental quality of product i and the indirect utility of a consumer (x, θ) derives from buying one unit of product i is given by:

$$U_{(x,\theta)}(l_i, q_i, p_i) = v + \theta q_i - t|x - l_i| - p_i \quad (1)$$

where $p_i$is the selling price of product i and v is the gross utility. In this model we assume that v is sufficiently large to ensure the market is fully covered, i.e., each consumer buys either one unit of product 1 or one unit of product 2. The transportation cost parameter t measures the level of horizontal differentiation (for consumers) between the two products. The larger the value of t, the more the two products are horizontally differentiated.

Both firms must comply with the minimum level of environmental quality established by the government which is denoted by q_{min}. Without loss of generality we normaliseq_{min} to zero in this model. As we have stated that environmental quality is often a credence goods that consumers cannot judge it on their own, there will be no incentive for firms to provide the products of higher environmental quality than the minimum level set by the government in the absence of environmental certification. Now consider that there exists an environmental certification agency specifies an environmental quality criteria $q_L > q_{min} (= 0)$. Each firm can choose to participate in the environmental certification and when the environmental quality of the product reaches this criteria, is awarded an eco-label. The existence of eco-label provides consumers the information of environmental quality, by assuring the consumer that producer has complied with predetermined criteria,q_L.

Each firm can provide product of environmental quality $q \in [0, \bar{q}]$ at a unit cost of $c(q)$, where $\bar{q}$ denotes the highest level of environmental quality that each firm can achieve in this industry. The unit cost $c(q)$ is monotonically increasing in environmental quality q. To pass the certification requires a firm to produce products with environmental quality q_L at a unit cost of $c(q_L)$, where $q_L \in [0, \bar{q}]$ is the certification criteria chosen by the certifier. However, if a firm chooses not to pursue the certification, she will set the environmental quality of her products at 0 (i.e., the minimum level of environmental quality required by the government) and incur a unit cost of $c(0)$. Letting $\omega(q_L) = c(q_L) - c(0)$ be the difference of unit cost between a certified product of environmental quality q_L and a uncertified product of environmental quality 0. Furthermore, in this model we assume that $\frac{\omega(q_L)}{q_L}$ is monotonically increasing with respect to q_L.

The timing of events is as follows:

1. In the first stage, the certifier announces its criteria for environmental certification, q_L.
2. In the second stage, observing the certification criteria, the two firms decide whether to pursue the environmental certification simultaneously and independently. Without loss of generality, we assume that if a firm is indifferent between being certified and being uncertified, she will choose to certify.

3. In the third stage, after observing each other's choice of whether or not to apply for the environmental certification, the two firms simultaneously determine the price of their products to compete in the market.
4. Finally, consumers decide which product to buy.

In what follows, we find the subgame-perfect Nash equilibrium by backward induction.

3. Consumer choice

We start with considering consumers purchase decision at the final stage. When the environmental qualities of both products are equal, i.e.,$q_1 = q_2$, then there is only horizontal differentiation between the two products. Thus, for any $\theta \in [0, 2\bar{\theta}]$, the marginal consumer who is indifferent between buying product 1 and product 2 is located at $\hat{x} = \frac{1}{2} - \frac{p_1 - p_2}{2t}$. Hence, the demand function of product i ($i = 1,2$) is given by:

$$D_i(p_1, p_2 | q_1 = q_2) = \frac{1}{2} - \frac{p_i - p_{3-i}}{2t} \tag{2}$$

Now consider the case that the environmental qualities of the two products are not equal. Without loss of generality, suppose that product 1 is certified while product 2 is uncertified, i.e.,$q_1 = q_L$ and $q_2 = 0$. In this case, the two products are horizontally and vertically differentiated. The marginal consumer who is indifferent between purchasing either of the two products is located in a position such that $v + \theta q_L - tx - p_1 = v - t(1-x) - p_2$ is satisfied. Thus, the market boundary is given by:

$$\hat{\theta}(x) = \frac{\Delta p - t}{q_L} + \frac{2t}{q_L} x \tag{3}$$

where $\Delta p = p_1 - p_2$ is the difference between the prices p_1 and p_2. Notice that $\hat{\theta}(x)$ is a linear increasing function of x. Furthermore, if Δp is very large (small), the market is partitioned into two parts – the consumers who buy from firm 1 and the consumers who buy from firm 2, as described in Figure 1.

The most interesting case occurs when Δp is a medium value where we can distinguish two possible scenarios: (1) horizontal dominance; and (2) vertical dominance, see Figure 2. In the scenario of horizontal dominance, both firms capture a positive market share for all $\theta \in [0, 2\hat{\theta}]$, see Figure 2(*a*). By contrast, when there is vertical dominance, the product of high environmental quality captures the entire market of consumers with high valuation of environmental quality, while the product of low environmental quality attracts all consumers with low valuation of environmental quality, see Figure 2(*b*). A moderate price-difference between the two products is also more realistic. In the following, we focus on the most interesting and realistic case where the price-difference Δp is medium.

In the scenario of horizontal dominance, the demand functions for product 1 and product 2 are respectively:

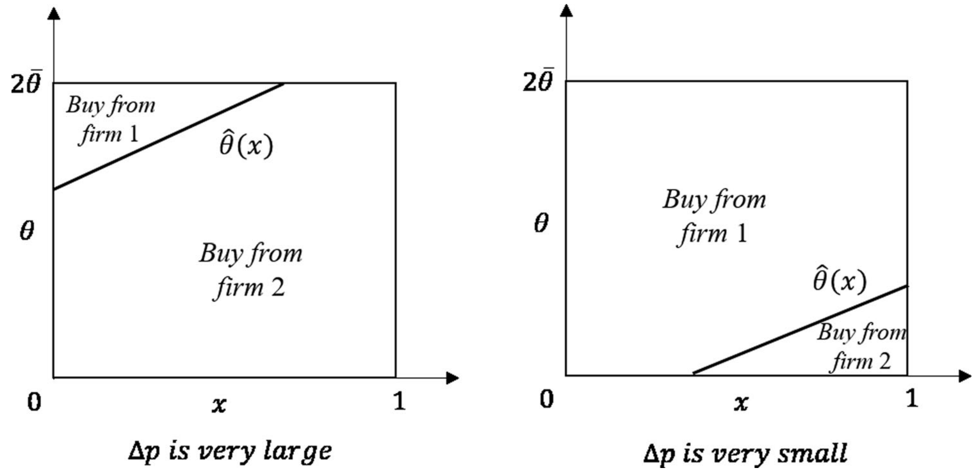

Figure 1. Partition of the market for large and small value of Δp. Source: The authors.

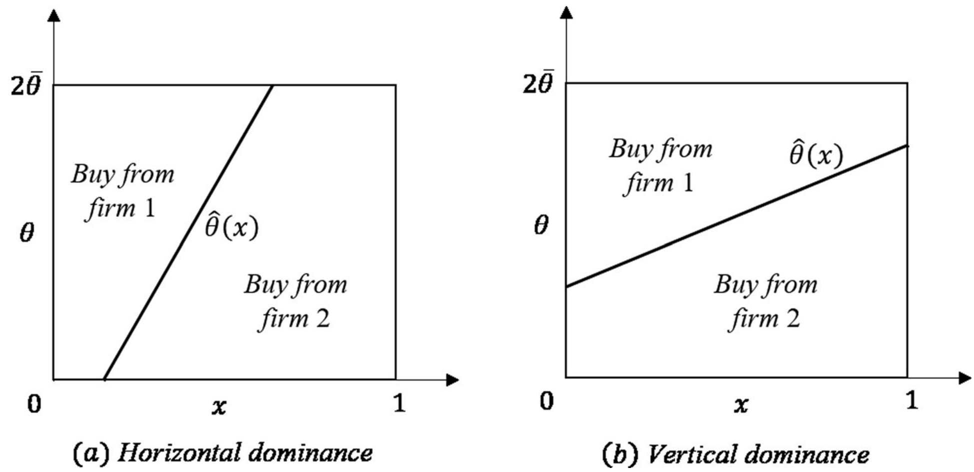

Figure 2. Partition of the market for medium value of Δp. Source: The authors.

$$\begin{cases} D_1^{HD}(p_1, p_2 | q_1 = q_L, q_2 = 0) = \dfrac{1}{2} - \dfrac{p_1 - p_2 - \bar{\theta} q_L}{2t} \\ D_2^{HD}(p_1, p_2 | q_1 = q_L, q_2 = 0) = \dfrac{1}{2} + \dfrac{p_1 - p_2 - \bar{\theta} q_L}{2t} \end{cases} \tag{4}$$

In the scenario of vertical dominance, the demand functions are respectively:

$$\begin{cases} D_1^{VD}(p_1, p_2 | q_1 = q_L, q_2 = 0) = 1 - \dfrac{p_1 - p_2}{2\bar{\theta} q_L} \\ D_1^{VD}(p_1, p_2 | q_1 = q_L, q_2 = 0) = \dfrac{p_1 - p_2}{2\bar{\theta} q_L} \end{cases}$$

$$\begin{cases} D_1^{VD}(p_1, p_2 | q_1 = q_L, q_2 = 0) = 1 - \dfrac{p_1 - p_2}{2\bar{\theta} q_L} \\ D_1^{VD}(p_1, p_2 | q_1 = q_L, q_2 = 0) = \dfrac{p_1 - p_2}{2\bar{\theta} q_L} \end{cases} \tag{5}$$

The superscripts *HD* and *VD* represent the scenario of horizontal dominance and the scenario of vertical dominance, respectively.

4. Price competition

In this section, we study the subgame in the third stage, i.e., after observing the certification outcome, each firm sets the price of her own product. Notice that there are three possible outcomes regarding the choices of whether or not to apply for the environmental certification by the two firms in the second stage, namely,

i. neither firm chooses to certify;
ii. both firms choose to certify;
iii. one firm chooses to certify while the other firm chooses not to certify.

4.1. Neither firm chooses to certify (NN case)

If both firms choose not to certify their products (referred to as *NN* case), they determine the environmental qualities of their products at the minimum environmental quality required by the government, i.e.,$q_1{=}q_2{=}0$. In this case the two products are pure horizontally differentiated and their demands are given by (2). In the second stage, each firm simultaneously and independently determines the selling price of her product in maximising $(p_i - c(0))\left(\frac{1}{2} - \frac{p_i - p_{3-i}}{2t}\right)$ which yields the following equilibrium prices and market shares:

$$\begin{cases} p_1^{NN\bullet} = p_2^{NN\bullet} = c(0) + t \\ D_1^{NN\bullet} = D_2^{NN\bullet} = \dfrac{1}{2} \end{cases} \tag{6}$$

And the equilibrium profit of each firm is $\pi_1^{NN\bullet} = \pi_1^{NN\bullet} = \frac{t}{2}$. Notice that as t increases, products are increasingly horizontal-differentiated (for consumers) and firms compete less fiercely which results in higher equilibrium prices and profits of both firms. However, the equilibrium market share of each firm is independent of the level of horizontal differentiation and each serves half the market.

4.2. Both firms choose to certify (CC case)

Now consider that both firms determine the environmental qualities of their products at q_L and apply for certification (referred to as *CC* case). As in *NN* case, in this case, there is also only horizontal differentiation between the two products. Each firm determines the selling price in maximising $(p_i - c(q_L))\left(\frac{1}{2} - \frac{p_i - p_{3-i}}{2t}\right)$ and yields the following equilibrium prices and market shares:

$$\begin{cases} p_1^{CC\bullet} = p_2^{CC\bullet} = c(q_L) + t \\ D_1^{CC\bullet} = D_2^{CC\bullet} = \dfrac{1}{2} \end{cases} \tag{7}$$

In this case, the equilibrium profit of each firm is $\pi_1^{CC\bullet} = \pi_1^{CC\bullet} = \frac{t}{2}$. We can observe that when both firms make symmetric choice whether or not to apply for the environmental certification, there is pure horizontal differentiation between their products and both firms set the same price, share the market equally and obtain the same profit.

4.3. A single firm chooses to certify (CN case)

In this subsection, we consider that the two firms make asymmetric decisions whether or not to apply for the environmental certification in the second stage. Without loss of generality, suppose that firm 1 chooses to certify while firm 2 chooses not to certify. In this case, the differentiation between the two products is both horizontal and vertical. As stated in the previous section, in this model we consider two possible scenarios: (1) *horizontal dominance*; and (2) *vertical dominance*.

In the scenario of horizontal dominance, the demands for the two products are given by (3). In the second stage, firm 1 and firm 2 determine the selling prices p_1 and p_2 simultaneously in maximisingtheir respective profits which are given by:

$$\begin{cases} \pi_1^{HD}(p_1) = (p_1 - c(q_L))\left(\dfrac{1}{2} - \dfrac{p_1 - p_2 - \bar{\theta} q_L}{2t}\right) \\ \pi_2^{HD}(p_2) = (p_2 - c(0))\left(\dfrac{1}{2} + \dfrac{p_1 - p_2 - \bar{\theta} q_L}{2t}\right) \end{cases} \tag{8}$$

The equilibrium prices can be derived from solving the first-order conditions and given by:

$$\begin{cases} p_1^{HD\bullet} = t + \dfrac{c(0) + 2c(q_L) + \bar{\theta} q_L}{3} \\ p_2^{HD\bullet} = t + \dfrac{2c(0) + c(q_L) - \bar{\theta} q_L}{3} \end{cases} \tag{9}$$

From (8), we can observe that the equilibrium prices of both products are increasing in both the level of horizontal differentiation and the unit cost of each product. Furthermore, when consumers' W.T.P. for environmental quality increases, the equilibrium price of the certified product improves whereas the uncertified firm charges a lower price in equilibrium.

Notice that the occurrence of horizontal dominance requires that the price-difference between the certified product and the uncertified product satisfies: $p_1 - p_2 \in [2\bar{\theta} q_L - t, t]$.

And from (8), we have $p_1^{HD\bullet} - p_2^{HD\bullet} = \frac{\omega(q_L)+2\bar{\theta}q_L}{3}$. Thus, to meet the above condition, the level of horizontal differentiation should satisfy: $t \geq max\left\{\frac{2\bar{\theta}q_L+\omega(q_L)}{3}, \frac{4\bar{\theta}q_L-\omega(q_L)}{3}\right\}$. This gives the following lemma.

Lemma 1. *When firm 1 chooses to certify while firm 2 chooses not to certify in the first stage, and if the level of horizontal differentiation satisfies* $t \geq max\left\{\frac{2\bar{\theta}q_L+\omega(q_L)}{3}, \frac{4\bar{\theta}q_L-\omega(q_L)}{3}\right\}$, *then in the second stage the equilibrium prices are given by (8).*

We refer to the above equilibrium as the horizontal dominance equilibrium since horizontal dominance occurs in this equilibrium. Notice that $max\left\{\frac{2\bar{\theta}q_L+\omega(q_L)}{3}, \frac{4\bar{\theta}q_L-\omega(q_L)}{3}\right\} \geq \bar{\theta}q_L$, thus a necessary condition for horizontal dominance equilibrium to occur is that the criteria chosen by the certifier must be sufficiently low, i.e.,$q_L \leq t\bar{\theta}$.

Substituting (8) into (3), the equilibrium market shares of the certified firm (i.e., firm 1) and the uncertified firm (i.e., firm 2) are respectively

$$\begin{cases} D_1^{HD\bullet} = \frac{1}{2} + \frac{\bar{\theta}q_L - \omega(q_L)}{6t} \\ D_2^{HD\bullet} = \frac{1}{2} - \frac{\bar{\theta}q_L - \omega(q_L)}{6t} \end{cases} \tag{10}$$

Recall that in absence of vertical differentiation, the equilibrium market share of each firm is independent of the level of horizontal differentiation and each firm serves half the market. When the two firms are both horizontally and vertically differentiated, from (9) we can observe that the effect of horizontal differentiation on market shares depends on the comparison of $\bar{\theta}q_L$ and $\omega(q_L)$. Specifically, when $\bar{\theta}q_L$ is higher (lower) than $\omega(q_L)$, as the level of horizontal differentiation increases, the certified firm will capture less (more) market share; whereas the uncertified firm will gain more (less) market share. Furthermore, if $\bar{\theta}q_L$ is higher than\$\omega(q_L)$, the equilibrium market share of the certified firm is larger than that of the uncertified firm, otherwise, the uncertified firm will occupy a larger market share.

Substituting (8) into (7), their equilibrium profits are given by:

$$\begin{cases} \pi_1^{HD\bullet} = \frac{\left[3t + \bar{\theta}q_L - \omega(q_L)\right]^2}{18t} \\ \pi_2^{HD\bullet} = \frac{\left[3t - \bar{\theta}q_L + \omega(q_L)\right]^2}{18t} \end{cases} \tag{11}$$

Proposition 1. *In horizontal dominance equilibrium,*

i. *the certified firm sets a higher price than the uncertified firm, i.e.,* $p_1^{HD\bullet} > p_2^{HD\bullet}$;
ii. *if* $\bar{\theta} \geq (\leq)\omega(q_L)/q_L$, *the certified firm captures a greater (smaller) market share and obtains higher (lower) profit than the uncertified firm, i.e.,* $D_1^{HD\bullet} \geq (\leq) D_2^{HD\bullet}$ *and* $\pi_1^{HD\bullet} \geq (\leq)\pi_2^{HD\bullet}$.

It is intuitive for the certified firm (i.e., firm 1) to charge higher price for its products, considering that certified products have higher unit costs and environmental quality. However, the firm that pursues environmental certification does not necessarily has a larger market share and higher profit. From Proposition 1, if the consumers' average W.T.P. for environmental quality is greater than $\omega(q_L)/q_L$, the certified firm will gain greater market share and obtain higher profit as compared with the uncertified firm. Otherwise, the uncertified firm will outperform the certified one in terms of market share and profit.

We now proceed to consider the scenario of vertical dominance. When there is vertical dominance, the demands for the two products are given by (4). The two firms determine the selling prices p_1 and p_2 simultaneously to maximise:

$$\begin{cases} \pi_1^{VD}(p_1) = (p_1 - c(q_L))\left(1 - \dfrac{p_1 - p_2}{2\bar{\theta} q_L}\right) \\ \pi_2^{VD}(p_2) = (p_2 - c(0))\left(\dfrac{p_1 - p_2}{2\bar{\theta} q_L}\right) \end{cases} \tag{12}$$

By solving the first-order conditions, the equilibrium prices in the scenario of vertical dominance are given by:

$$\begin{cases} p_1^{VD\bullet} = \dfrac{c(0) + 2c(q_L) + 4\bar{\theta} q_L}{3} \\ p_2^{VD\bullet} = \dfrac{2c(0) + c(q_L) + 2\bar{\theta} q_L}{3} \end{cases} \tag{13}$$

From (13), the equilibrium prices in the scenario of vertical dominance are independent of the level of horizontal differentiation (t). Interestingly, we find that in this scenario both firms will charge higher prices as consumers' W.T.P. on environmental quality improves. Recall that in the scenario of horizontal dominance, as $\bar{\theta}$ increases, only the certified firm improves its price whereas the uncertified firm lowers its selling price.

The occurrence of vertical dominance requires that the price-difference satisfies: $p_1 - p_2 \in [t, 2\bar{\theta} q_L - t]$. From (10), we have $p_1^{VD\bullet} - p_2^{VD\bullet} = \frac{\omega(q_L) + 2\bar{\theta} q_L}{3}$. Hence, to meet the above condition, the level of horizontal differentiation should satisfy: $t \leq min\left\{\frac{2\bar{\theta} q_L + \omega(q_L)}{3}, \frac{4\bar{\theta} q_L - \omega(q_L)}{3}\right\}$. This gives the following lemma.

Lemma 2. *When firm 1 chooses to certify while firm 2 chooses not to certify in the first stage, and if the level of horizontal differentiation satisfies* $t \leq min\left\{\frac{2\bar{\theta} q_L + \omega(q_L)}{3}, \frac{4\bar{\theta} q_L - \omega(q_L)}{3}\right\}$, *then in the second stage the equilibrium prices are given by (13).*

We refer to the above equilibrium as the vertical dominance equilibrium since vertical dominance occurs in this equilibrium. Also note that $min\left\{\frac{2\bar{\theta} q_L + \omega(q_L)}{3}, \frac{4\bar{\theta} q_L - \omega(q_L)}{3}\right\}$, thus a necessary condition for vertical dominance equilibrium to occur is that the criteria chosen by the certifier must be sufficiently high, i.e., $q_L \geq t\bar{\theta}$.

Substituting (13) into (4), the equilibrium market shares in the scenario of vertical dominance are respectively:

$$\begin{cases} D_1^{VD\bullet} = \dfrac{2}{3} - \dfrac{\omega(q_L)}{6\bar{\theta}q_L} \\ D_2^{VD\bullet} = \dfrac{1}{3} + \dfrac{\omega(q_L)}{6\bar{\theta}q_L} \end{cases} \tag{14}$$

From (14), in the scenario of vertical dominance, the equilibrium market share of the certified firm is not greater than 2/3, and the equilibrium market share of the uncertified firm is not lower than 1/3. Furthermore, as consumers' W.T.P. for environmental quality increases, the market share of the certified firm will increase while the demand for the uncertified products will decline. When the certifier sets a higher criteria, the certified firm's market share will decrease whereas the uncertified firm will expand its market share since $\frac{\omega(q_L)}{q_L}$ is monotonically increasing in q_L.

Substituting (13) into (12), the respective equilibrium profits of the certified firm and the uncertified firm are given by:

$$\begin{cases} \pi_1^{VD\bullet} = \dfrac{\left[4\bar{\theta}q_L - \omega(q_L)\right]^2}{18\bar{\theta}q_L} \\ \pi_2^{VD\bullet} = \dfrac{\left[2\bar{\theta}q_L + \omega(q_L)\right]^2}{18\bar{\theta}q_L} \end{cases} \tag{15}$$

Proposition 2. *In vertical dominance equilibrium,*

i. *the certified firm sets a higher price than the uncertified firm, i.e.,* $p_1^{VD\bullet} > p_2^{VD\bullet}$;
ii. *if* $\bar{\theta} \geq (\leq)\omega(q_L)/q_L$, *the certified firm captures a greater (smaller) market share and has higher (lower) profit than the uncertified firm, i.e.,* $D_1^{VD\bullet} \geq (\leq) D_2^{VD\bullet}$ and $\pi_1^{VD\bullet} \geq (\leq) \pi_2^{VD\bullet}$.

From Propositions 1 and 2, we can observe that in both cases of horizontal dominance and vertical dominance the certified firm chooses a higher price than the uncertified one. Furthermore, the certified firm can grab a larger market share and earn higher profit if consumers' average W.T.P. for environmental quality ($\bar{\theta}$) is greater than the ratio $\omega(q_L)/q_L$.

Proposition 3. *As compared with horizontal dominance equilibrium, in vertical dominance equilibrium,*

i. *the selling prices of both products are higher, i.e.,* $p_i^{VD\bullet} \geq p_i^{HD\bullet}$, i = 1,2;

Table 1. Equilibrium profits when $t \geq max\left\{\frac{2\bar{\theta}q_L+\omega(q_L)}{3}, \frac{4\bar{\theta}q_L-\omega(q_L)}{3}\right\}$.

	Not to certify	To certify
Not to certify	$\frac{t}{2}, \frac{t}{2}$	$\frac{[3t-\bar{\theta}q_L+(q_L)]^2}{18t}, \frac{[3t+\bar{\theta}q_L+(q_L)]^2}{18t}$
To certify	$\frac{[3t+\bar{\theta}q_L-\omega(q_L)]^2}{18t}, \frac{[3t-\bar{\theta}q_L+\omega(q_L)]^2}{18t}$	$\frac{t}{2}, \frac{t}{2}$

Source: The authors.

ii. *if* $\bar{\theta} \geq (\leq)\omega(q_L)/q_L$, *the market share of the certified firm (i.e., firm 1) is larger (smaller), i.e.,* $D_1^{VD\bullet} \geq (\leq)D_1^{HD\bullet}$, *whereas the market share of the uncertified firm (i.e., firm 2) is smaller (larger), i.e.,* $D_2^{VD\bullet} \leq (\geq)D_2^{HD\bullet}$.

Notice that in vertical dominance equilibrium, the certification criteria is stricter than that in horizontal dominance equilibrium. Thus, the environmental quality of the certified products is higher than that in horizontal dominance equilibrium. Hence, the level of vertical differentiation is higher in vertical dominance equilibrium which weakens the competition between the two firms. Therefore, the equilibrium prices of both the certified products and the uncertified products are higher in vertical dominance equilibrium. In terms of the market share, from Proposition 3, we can see that the market share of the certified (uncertified) firm in vertical dominance equilibrium is larger (smaller) than that in horizontal dominance equilibrium if consumers' average W.T.P. for environmental quality is higher than $\omega(q_L)/q_L$. Otherwise, the certified (uncertified) firm gains greater (smaller) market share in horizontal dominance equilibrium than in vertical dominance equilibrium.

5. To certify or not to certify

In this section we consider the problem facing the two firms in the second stage, i.e., given the certification criteria chosen by the certifier, they simultaneously and independently decide whether or not to apply for the environmental certification. Without loss of generality, we assume that if a firm is indifferent between being certified and being uncertified, the firm chooses to certify.

If the level of horizontal differentiation between the two firms satisfies $t \geq max\left\{\frac{2\bar{\theta}q_L+\omega(q_L)}{3}, \frac{4\bar{\theta}q_L-\omega(q_L)}{3}\right\}$, the equilibrium profits of the two firms corresponding to their choices whether to certify or not are provided in Table 1.

Let $q_{\bar{\theta}}$ be the level of environmental quality that satisfies $\frac{\omega(q_{\bar{\theta}})}{q_{\bar{\theta}}} = \bar{\theta}$, we have the following proposition.

Proposition 4. *Given the level of horizontal differentiation and the certification criteria satisfies* $t \geq max\left\{\frac{2\bar{\theta}q_L+\omega(q_L)}{3}, \frac{4\bar{\theta}q_L-\omega(q_L)}{3}\right\}$,

i. *if the criteria chosen by the certifier* $q_L \leq q_{\bar{\theta}}$, *both firms choose to apply for certification in equilibrium (CC equilibrium);*
ii. *if the criteria chosen by the certifier* $q_L > q_{\bar{\theta}}$, *both firms choose not to apply for certification in equilibrium (NN equilibrium);*
iii. *CN case never occurs in equilibrium.*

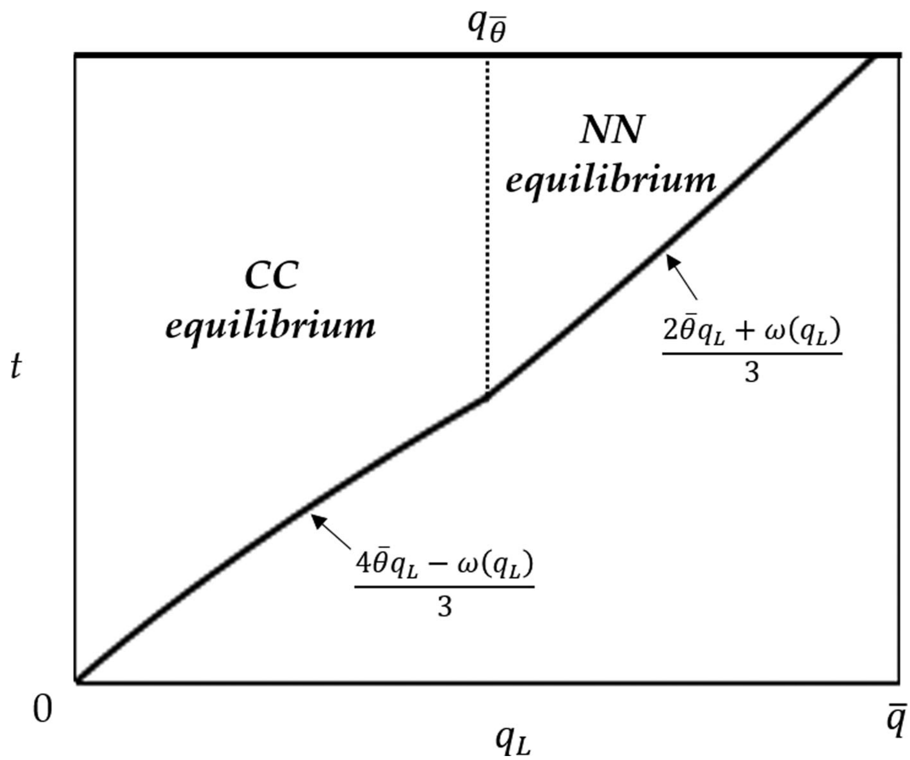

Figure 3. Equilibria when $t \geq max\left\{\frac{2\bar{\theta}q_L+\omega(q_L)}{3}, \frac{4\bar{\theta}q_L-\omega(q_L)}{3}\right\}$. Source: The authors.

The proposition shows that when the level of horizontal differentiation between the two firms exceeds a threshold, there exists only the symmetric equilibrium where both firms choose to or both choose not to certify their products. In other words, asymmetric equilibrium where only one firm chooses to certify never occurs in this case. This implies that when the two products are sufficiently differentiated in the horizontal dimension it is not attractive for firms to achieve vertical differentiation through investments in environmental quality. In this case the two firms apply for environmental certification simply because the certification is easy to pass, i.e., the criteria set by the certifier is sufficiently low ($q_L \leq q_{\bar{\theta}}$). If the criteria q_L exceeds $q_{\bar{\theta}}$, neither firm will participate in the environmental certification. We illustrate the equilibria that occur when $t \geq max\left\{\frac{2\bar{\theta}q_L+\omega(q_L)}{3}, \frac{4\bar{\theta}q_L-\omega(q_L)}{3}\right\}$ in Figure 3, where *CC* equilibrium represents that both firms choose to apply for certification in equilibrium, and *NN* equilibrium represents that neither firm chooses to certify in equilibrium. In Figure 3, we can observe that in the scenario where $t \geq max\left\{\frac{2\bar{\theta}q_L+\omega(q_L)}{3}, \frac{4\bar{\theta}q_L-\omega(q_L)}{3}\right\}$, the change in the level of horizontal differentiation does not affect the incentives for two firms to participate in the environmental certification. Indeed, in this scenario the two firms both choose to pursue the certification if the criteria q_L is sufficiently low, while if q_L exceeds the threshold $q_{\bar{\theta}}$ they both reject the environmental certification.

Table 2. Equilibrium profits when $t \leq min\left\{\frac{2\bar{\theta}q_L+\omega(q_L)}{3}, \frac{4\bar{\theta}q_L-\omega(q_L)}{3}\right\}$.

	Not to certify	To certify
Not to certify	$\frac{t}{2}, \frac{t}{2}$	$\frac{[2\bar{\theta}q_L+\omega(q_L)]^2}{18\bar{\theta}q_L}, \frac{[4\bar{\theta}q_L-\omega(q_L)]^2}{18\bar{\theta}q_L}$
To certify	$\frac{[4\bar{\theta}q_L-\omega(q_L)]^2}{18\bar{\theta}q_L}, \frac{[2\bar{\theta}q_L+\omega(q_L)]^2}{18\bar{\theta}q_L}$	$\frac{t}{2}, \frac{t}{2}$

Source: The authors.

If the level of horizontal differentiation satisfies $t \leq min\left\{\frac{2\bar{\theta}q_L+\omega(q_L)}{3}, \frac{4\bar{\theta}q_L-\omega(q_L)}{3}\right\}$, the equilibrium profits of the two firms corresponding to their choices whether to apply for the environmental certification are shown in Table 2.

Proposition 5. *Given the level of horizontal differentiation and the certification criteria satisfies* $t \leq min\left\{\frac{2\bar{\theta}q_L+\omega(q_L)}{3}, \frac{4\bar{\theta}q_L-\omega(q_L)}{3}\right\}$,

i. *if the criteria chosen by the certifier* $q_L \leq q_{\bar{\theta}}$, *both firms choose to apply for certification in equilibrium (CC equilibrium) when* $t \in \left[\frac{[2\bar{\theta}q_L+\omega(q_L)]^2}{9\bar{\theta}q_L}, \frac{2\bar{\theta}q_L+\omega(q_L)}{3}\right]$, *a single firm chooses to apply for certification in equilibrium (vertical dominance equilibrium) when* $t < \frac{[2\bar{\theta}q_L+\omega(q_L)]^2}{9\bar{\theta}q_L}$, *and NN case never occurs in equilibrium.*
ii. *if the criteria chosen by the certifier* $q_L > q_{\bar{\theta}}$, *both firms choose not to apply for certification in equilibrium (NN equilibrium) when* $t \in \left[\frac{[4\bar{\theta}q_L-\omega(q_L)]^2}{9\bar{\theta}q_L}, \frac{4\bar{\theta}q_L-\omega(q_L)}{3}\right]$, *a single firm chooses to apply for certification in equilibrium (vertical dominance equilibrium) when* $t \leq \frac{[4\bar{\theta}q_L-\omega(q_L)]^2}{9\bar{\theta}q_L}$, *and CC case never occurs in equilibrium.*

From Proposition 5 we can see that asymmetric equilibrium where a single firm chooses to certify in equilibrium can possibly occur if the level of horizontal differentiation between the two products is sufficiently low, i.e., $t \leq min\left\{\frac{2\bar{\theta}q_L+\omega(q_L)}{3}, \frac{4\bar{\theta}q_L-\omega(q_L)}{3}\right\}$. Recall that in the case that the level of horizontal differentiation is sufficiently high ($t \geq max\left\{\frac{2\bar{\theta}q_L+\omega(q_L)}{3}, \frac{4\bar{\theta}q_L-\omega(q_L)}{3}\right\}$) asymmetric equilibrium never occurs. This implies that in the case that the level of horizontal differentiation between the two products is sufficiently low, the firms have incentives to pursue vertical differentiation through environmental certification. Furthermore, the asymmetric equilibrium that occurs in the scenario where $t \leq min\left\{\frac{2\bar{\theta}q_L+\omega(q_L)}{3}, \frac{4\bar{\theta}q_L-\omega(q_L)}{3}\right\}$ is *vertical dominance equilibrium*. As we have stated that in the scenario where $t \geq max\left\{\frac{2\bar{\theta}q_L+\omega(q_L)}{3}, \frac{4\bar{\theta}q_L-\omega(q_L)}{3}\right\}$, the change in the level of horizontal differentiation does not influence the incentives for the two firms to apply for the environmental certification. By contrast, when $t \leq min\left\{\frac{2\bar{\theta}q_L+\omega(q_L)}{3}, \frac{4\bar{\theta}q_L-\omega(q_L)}{3}\right\}$, we observe that the increase in horizontal differentiation between the two firms can promote or hinder the adoption of environmental certification in this industry. Specifically, if the certification

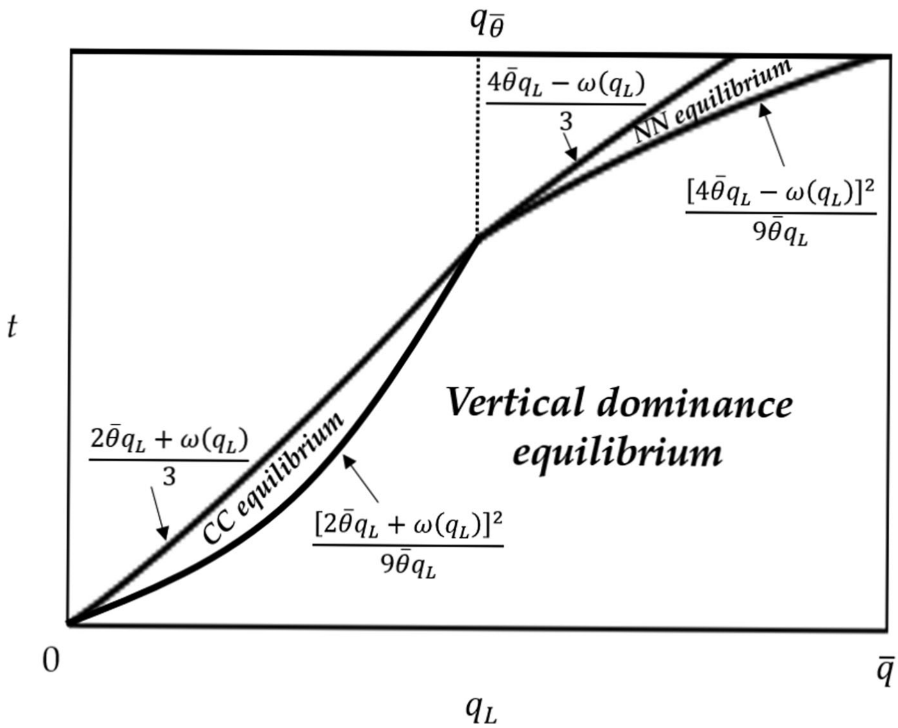

Figure 4. Equilibria when $t \leq min\left\{\frac{2\bar{\theta}q_L+\omega(q_L)}{3}, \frac{4\bar{\theta}q_L-\omega(q_L)}{3}\right\}$. Source: The authors.

criteria $q_L \leq q_{\bar{\theta}}$, the increase in the horizontal differentiation between the two firms can transform the equilibrium from vertical dominance equilibrium (where a single firm is certified) to *CC* equilibrium (where both firms are certified). However, when the certification criteria $q_L > q_{\bar{\theta}}$, the increase in the level of horizontal differentiation can change the equilibrium from vertical dominance equilibrium (where a single firm is certified) to *NN* equilibrium (where neither firm is certified). We illustrate the equilibria that occur when $t \leq min\left\{\frac{2\bar{\theta}q_L+\omega(q_L)}{3}, \frac{4\bar{\theta}q_L-\omega(q_L)}{3}\right\}$ in Figure 4.

6. Conclusion

Environmental certification serves as a means to distinguish the products of high environmental quality from those uncertified products of low environmental quality. In this articlewe suppose that consumers prefer environment friendly products, but they are heterogeneous in their W.T.P. for environmental quality. Furthermore, we incorporate horizontal product differentiation in our model and thus propose a model combining both horizontal and vertical differentiation to account for two-dimensional competition.

Using this framework, we have studied the price competition between the two firms and their decisions whether to apply for the environmental certification or not. The results show that when the level of horizontal differentiation relative to the degree of vertical differentiation is sufficiently high, there exist only the symmetric equilibria where both firms choose to or both choose not to certify their products. Asymmetric equilibrium where a single firm opts for the certification occurs when the level of horizontal differentiation relative to the degree of vertical differentiation is sufficiently low.

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Appendix

Proof of Lemma 1. In CN case, when there is horizontal dominance, the respective profit functions of the certified firm (firm 1) and the uncertified firm (firm 2) are given in (7). F.O.C.s are given by:

$$\begin{cases} \dfrac{\partial \pi_1^{HD}}{\partial p_1} = \dfrac{c(q_L) - 2p_1 + p_2 + \bar{\theta} q_L + t}{2t} = 0 \\ \dfrac{\partial \pi_2^{HD}}{\partial p_2} = \dfrac{c(0) + p_1 - 2p_2 - \bar{\theta} q_L + t}{2t} = 0 \end{cases}$$

Solving F.O.C.s gives:

$$\begin{cases} p_1^{HD*} = t + \dfrac{c(0) + 2c(q_L) + \bar{\theta} q_L}{3} \\ p_2^{HD*} = t + \dfrac{2c(0) + c(q_L) - \bar{\theta} q_L}{3} \end{cases}$$

Notice that the occurrence of horizontal dominance requires that the price-difference $p_1 - p_2 \in [2\bar{\theta} q_L - t, t]$, thus (p_1^{HD*}, p_2^{HD*}) is an equilibrium only when the following inequalities hold, i.e.:

$$2\bar{\theta} q_L - t \le \frac{\omega(q_L) + 2\bar{\theta} q_L}{3} \le t$$

or equivalently, $t \ge max\left\{\frac{2\bar{\theta} q_L + \omega(q_L)}{3}, \frac{4\bar{\theta} q_L - \omega(q_L)}{3}\right\}$.

Proof of Proposition 1. Notice that $p_1^{HD*} - p_2^{HD*} = \frac{\omega(q_L) + 2\bar{\theta} q_L}{3} > 0$, thus $p_1^{HD*} > p_2^{HD*}$. From (9), we have $D_1^{HD*} - D_2^{HD*} = \frac{\bar{\theta} q_L - \omega(q_L)}{3t} \gtreqless 0 \Longleftrightarrow \bar{\theta} q_L \gtreqless \omega(q_L)$. From (10), we have

$$\pi_1^{HD*} \gtreqless \pi_2^{HD*} \Longleftrightarrow \left[3t + \bar{\theta} q_L - \omega(q_L)\right]^2 \gtreqless \left[3t - \bar{\theta} q_L + \omega(q_L)\right]^2 \Longleftrightarrow \bar{\theta} q_L \gtreqless \omega(q_L)$$

Proof of Lemma 2. The proof is similar to Lemma 1 and thus omitted.

Proof s of Propositions 2 and 3.
The proofs are similar to Proposition 1 and thus omitted.

Proof of Proposition 4. When the level of horizontal differentiation satisfies $t \ge max\left\{\frac{2\bar{\theta} q_L + \omega(q_L)}{3}, \frac{4\bar{\theta} q_L - \omega(q_L)}{3}\right\}$, the equilibrium profits of the two firms responding to their choices whether to certify or not are provided in Table 1. (Not to certify, Not to certify) is a Nash equilibrium if any firm has no incentive to certify given that the other firm remains uncertified, and this requires:

$$\frac{t}{2} > \frac{\left[3t + \bar{\theta} q_L - \omega(q_L)\right]^2}{18t} \Longleftrightarrow \bar{\theta} < \frac{\omega(q_L)}{q_L}$$

Letting $\frac{\omega(q_{\bar{\theta}})}{q_{\bar{\theta}}}=\theta$, and since $\frac{\omega(q_L)}{q_L}$ is monotonically increasing with respect toq_L, then:

$$\frac{\bar{\theta}<\frac{\omega(q_L)}{q_L} \Longleftrightarrow \omega(q_{\bar{\theta}})}{q_{\bar{\theta}}<\frac{\omega(q_L)}{q_L} \Longleftrightarrow q_L>q_{\bar{\theta}}}$$

(To certify, Not to certify) or (Not to certify, To certify) is a Nash equilibrium only when the following inequalities are satisfied simultaneously:

$$\begin{cases} \frac{\left[3t+\bar{\theta}q_L-\omega(q_L)\right]^2}{18t} \geq \frac{t}{2} \\ \frac{\left[3t-\bar{\theta}q_L+\omega(q_L)\right]^2}{18t} > \frac{t}{2} \end{cases} \Longleftrightarrow \begin{cases} \bar{\theta} \geq \frac{\omega(q_L)}{q_L} \\ \bar{\theta}<\frac{\omega(q_L)}{q_L} \end{cases}$$

Hence, (To certify, Not to certify) or (Not to certify, To certify) is never a Nash equilibrium, i.e., CN case never occurs in equilibrium.

Proof of Proposition 5. When $t \leq min\left\{\frac{2\bar{\theta}q_L+\omega(q_L)}{3}, \frac{4\bar{\theta}q_L-\omega(q_L)}{3}\right\}$, the equilibrium profits of the two firms responding to their choices whether to certify or not are provided in Table 2. Notice that:

$$min\left\{\frac{2\bar{\theta}q_L+\omega(q_L)}{3}, \frac{4\bar{\theta}q_L-\omega(q_L)}{3}\right\} = \left\{ \frac{4\bar{\theta}q_L-\omega(q_L)}{3}, if q_L>q_{\bar{\theta}} \quad \frac{2\bar{\theta}q_L+\omega(q_L)}{3}, if q_L \leq q_{\bar{\theta}} \right.$$

(Not to certify, Not to certify) is a Nash equilibrium requires:

$$\frac{t}{2} > \frac{\left[4\bar{\theta}q_L-\omega(q_L)\right]^2}{18\bar{\theta}q_L} \Longleftrightarrow t > \frac{\left[4\bar{\theta}q_L-\omega(q_L)\right]^2}{9\bar{\theta}q_L}$$

Hence, if $q_L>q_{\bar{\theta}}$, NN equilibrium occurs when $t \in \left[\frac{[4\bar{\theta}q_L-\omega(q_L)]^2}{9\bar{\theta}q_L}, \frac{4\bar{\theta}q_L-\omega(q_L)}{3}\right]$. Notice that $\left(\frac{[4\bar{\theta}q_L-\omega(q_L)]^2}{9\bar{\theta}q_L}, \frac{4\bar{\theta}q_L-\omega(q_L)}{3}\right)$ is not empty set since

$$\frac{\left[4\bar{\theta}q_L-\omega(q_L)\right]^2}{9\bar{\theta}q_L} < \frac{4\bar{\theta}q_L-\omega(q_L)}{3} \Longleftrightarrow \bar{\theta}<\frac{\omega(q_L)}{q_L} \Longleftrightarrow q_L>q_{\bar{\theta}}$$

If $q_L \leq q_{\bar{\theta}}$, NN equilibrium occurs when $t \in \left(\frac{[4\bar{\theta}q_L-\omega(q_L)]^2}{9\bar{\theta}q_L}, \frac{2\bar{\theta}q_L+\omega(q_L)}{3}\right]$. Notice that $\left(\frac{[4\bar{\theta}q_L-\omega(q_L)]^2}{9\bar{\theta}q_L}, \frac{2\bar{\theta}q_L+\omega(q_L)}{3}\right]$ is empty set since $\frac{[4\bar{\theta}q_L-\omega(q_L)]^2}{9\bar{\theta}q_L} < \frac{2\bar{\theta}q_L+\omega(q_L)}{3} \Longleftrightarrow (\bar{\theta}q_L-\omega(q_L))(10\bar{\theta}q_L-\omega(q_L))<0$ which is contradict to $\bar{\theta} \geq \frac{\omega(q_L)}{q_L}$. Thus, NN equilibrium never occurs if $q_L \leq q_{\bar{\theta}}$.

(To certify, To certify) is a Nash equilibrium requires:

$$\frac{t}{2} \geq \frac{\left[2\bar{\theta}q_L+\omega(q_L)\right]^2}{18\bar{\theta}q_L} \Longleftrightarrow t \geq \frac{\left[2\bar{\theta}q_L+\omega(q_L)\right]^2}{9\bar{\theta}q_L}$$

Hence, if $q_L>q_{\bar{\theta}}$, CC equilibrium occurs when $t \in \left[\frac{[2\bar{\theta}q_L+\omega(q_L)]^2}{9\bar{\theta}q_L}, \frac{4\bar{\theta}q_L-\omega(q_L)}{3}\right]$. Notice that $\left[\frac{[2\bar{\theta}q_L+\omega(q_L)]^2}{9\bar{\theta}q_L}, \frac{4\bar{\theta}q_L-\omega(q_L)}{3}\right]$ is empty set since

$$\frac{\left[2\bar{\theta}q_L + \omega(q_L)\right]^2}{9\bar{\theta}q_L} \le \frac{4\bar{\theta}q_L - \omega(q_L)}{3} \Longleftrightarrow (\bar{\theta}q_L - \omega(q_L))(8\bar{\theta}q_L + \omega(q_L)) \ge 0 \Longleftrightarrow \bar{\theta}q_L \ge \omega(q_L)$$

which is contradict to $\bar{\theta} < \frac{\omega(q_L)}{q_L}$. Thus, CC equilibrium never occurs if $q_L > q_{\bar{\theta}}$.

If $q_L \le q_{\bar{\theta}}$, CC equilibrium occurs when $t \in \left[\frac{[2\bar{\theta}q_L + \omega(q_L)]^2}{9\bar{\theta}q_L}, \frac{2\bar{\theta}q_L + \omega(q_L)}{3}\right]$. Notice that $\left[\frac{[2\bar{\theta}q_L + \omega(q_L)]^2}{9\bar{\theta}q_L}, \frac{2\bar{\theta}q_L + \omega(q_L)}{3}\right]$ is not empty set since

$$\frac{\left[2\bar{\theta}q_L + \omega(q_L)\right]^2}{9\bar{\theta}q_L} \le \frac{2\bar{\theta}q_L + \omega(q_L)}{3} \Longleftrightarrow \bar{\theta} \ge \frac{\omega(q_L)}{q_L} \Longleftrightarrow q_L \le q_{\bar{\theta}}.$$

(To certify, Not to certify) or (Not to certify, To certify) is a Nash equilibrium only when the following inequalities are satisfied simultaneously:

$$\begin{cases} \dfrac{\left[4\bar{\theta}q_L - \omega(q_L)\right]^2}{18\bar{\theta}q_L} \ge \dfrac{t}{2} \\ \dfrac{\left[2\bar{\theta}q_L + \omega(q_L)\right]^2}{18\bar{\theta}q_L} > \dfrac{t}{2} \end{cases} \Longleftrightarrow \begin{cases} t \le \dfrac{\left[4\bar{\theta}q_L - \omega(q_L)\right]^2}{9\bar{\theta}q_L} \\ t < \dfrac{\left[2\bar{\theta}q_L + \omega(q_L)\right]^2}{9\bar{\theta}q_L} \end{cases}$$

Notice that if $q_L > q_{\bar{\theta}}$, we have

$$\frac{\left[4\bar{\theta}q_L - \omega(q_L)\right]^2}{9\bar{\theta}q_L} < \frac{\left[2\bar{\theta}q_L + \omega(q_L)\right]^2}{9\bar{\theta}q_L} < \frac{4\bar{\theta}q_L - \omega(q_L)}{3} < \frac{2\bar{\theta}q_L + \omega(q_L)}{3}$$

Hence, if $q_L > q_{\bar{\theta}}$, CN equilibrium occurs when $t \le \frac{[4\bar{\theta}q_L - \omega(q_L)]^2}{9\bar{\theta}q_L}$.
If $q_L \le q_{\bar{\theta}}$, we have

$$\frac{\left[2\bar{\theta}q_L + \omega(q_L)\right]^2}{9\bar{\theta}q_L} < \frac{\left[4\bar{\theta}q_L - \omega(q_L)\right]^2}{9\bar{\theta}q_L} < \frac{2\bar{\theta}q_L + \omega(q_L)}{3} < \frac{4\bar{\theta}q_L - \omega(q_L)}{3}$$

Hence, if $q_L \le q_{\bar{\theta}}$, CN equilibrium occurs when $t < \frac{[2\bar{\theta}q_L + \omega(q_L)]^2}{9\bar{\theta}q_L}$.