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Oligopoly Studies: On the Interaction of Private Firms with Homogeneous and Heterogeneous Objectives

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Declaration of Authorship

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- Where I have consulted the published work of others, this is always clearly attributed.
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Mariel Adriana Leal Coronado
Monterrey Nuevo León, May 14th, 2018

Dedication

To my beloved God and my beautiful family.

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Oligopoly studies: On the interaction of private firms with homogeneous and heterogeneous objectives.

By

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Abstract

Two oligopoly studies compose this thesis. The first study considers that firms have the homogenous objective of maximizing their profits. The second one contemplates the presence of a private firm with a different objective, a consumer-friendly firm.

In detail, in the second chapter, the effects of uniting two separated markets each monopolized initially by a producer into a globalized duopoly market are studied. A linear inverse demand with cap price and quadratic cost functions is considered. After globalization, the Consistent Conjectural Variations Equilibrium of the duopoly game is found. Unlike the Cournot Equilibrium, complete symmetry (same cost function's parameters of both firms) does not represent the strongest coincident profit degradation. When both firms are low-marginal cost firms, it is found that the firm with a technical advantage over her rival has a better ratio and as the rival becomes weaker, this is, as the slope of the rival's marginal cost function increases, the profit ratio improves.

In the third chapter, the study considers a Cournot duopoly model with a consumer-friendly firm and analyzes the interplay between the strategic choice of abatement technology and the timing of government's commitment to the environmental tax policy. It is shown that the optimal emission tax under committed policy regime is always higher than that under non-committed one, but both taxes can be higher than marginal environmental damage when the consumer-friendliness is high enough. It is also shown that the emergence of a consumer-friendly firm might yield better outcomes to both welfare and environmental quality without the commitment to the environmental policy.

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Chapter 1.

Introduction

This thesis studies the economic effects of the interaction of a few companies contextualized in the implementation of different public policies. An industry composed of a small number of firms that produce specific good competing to satisfy the market demand is called oligopoly. Oligopoly models, generally assume that private firms have homogenous objectives: to maximize its profits. In the modern economy, some firms have other motivations as well. There are firms which are more involved with society: concerned about their consumers, their workers or the environment. These kinds of firms are known as non-profit organizations, corporate social responsible firms (or specifically, consumer-friendly firms if they have pro-consumer interests). Here both types of interactions are studied: the classic oligopoly game where the firms have the same objective and the mixed oligopoly where the firms have some other interests plus its profits.

To model the implementation of the public policies, multi-level games are formulated. The players make their decisions to maximize their payoff functions. The equilibrium for each game is found given the public policy to be investigated and the homogeneity and heterogeneity of the objectives of the companies. Finally, the consequences for companies in the game of the first study and society and the environment quality in the second study are analyzed. The results of this research shall be taken into account by governments when designing public policies and by companies when making their decisions.

1.1 Motivation

The oligopoly models are studied due to its relevance within Industrial Organization and policy-making. The oligopoly is a very prominent market structure; they can be noticed, for example, the following industries: Cable Television, Streaming services, Smartphones' Operating Systems, Airline industry, Pharmaceutical, Oil and Gas, Automotive industry, etc. Through the study of oligopoly models, it is possible to analyze the effects of different public policies and develop the fundaments for the implementation of such systems.

Chapter 2, through an oligopoly model, examines the effects that globalizing separated monopolies into a single market would have on firm's profit. In a single market, countries allow the movement of goods within the countries' union as if it were a single country.

This research is relevant mainly to the firms of countries participating in free trade policies since it explains the effects that globalization would have on its profit considering the asymmetry in costs. A particular example of an industry dominated by few companies affected by globalization is the automotive industry. The companies are a fundamental part of the development of a country's economy.

Therefore, it becomes relevant to know the impact of such an agreement on the firms' performance. Governments should take into account firms' performance while policy-making (especially Ministry of Economy).

Chapter 3 studies the timing of government's commitment to the implementation of environmental tax policy. This analysis is made regarding society's welfare and the environmental quality. For this study, the heterogeneity of the objectives of the firms is highlighted, by considering that one of them is socially responsible. This social responsibility is displayed by not only maximizing its profit but also adding to its objective a portion of Consumer Surplus. This kind of firms is also known as "consumer-friendly." CSR initiatives play a significant role in the design and implementation of the environmental policy.

This research is essential for polluting companies; for example, automobile manufacturing and oil and gas are carbon-intensive industries. Carbon taxes are currently being considered or implemented around the world. This research is particularly significant for the policy-makers.

1.2 Problem Statement and Context

There are a large number of industries whose structure corresponds to that of an oligopoly. Unlike perfect competition (where firms are price takers), or the monopoly (one company), in an oligopoly, the decisions of one firm have an effect on the other companies. Due to the common nature of this type of market structure, it is necessary to study it in the context of public policies 'development, be it the opening of markets or the implementation of environmental policies. This thesis examines the interaction of private companies in different contexts:
1) Effects of globalization under consistent conjectural variations, where we assume that firms have homogeneous objectives; and
2) The timing of environmental tax policy with a consumer-friendly firm, for which a classic Cournot model is used, and the firms have different objectives.

1.2.1 Effects of Globalization under Consistent Conjectures

This chapter addresses the impact that the union of separate markets into a globalized single market has on firms' profit. In particular, the conditions under which globalization is not good for a company are sought.

The world's economy is moving towards high levels of globalization. Some countries have created alliances with the aim of establishing a single market. One remarkable example is The European Union, which set the single market since the 90s. A single market represents more significant business opportunities for the companies, as well as having access to a larger number of customers and suppliers. Meanwhile, consumers would be expected to benefit from more competitive prices.

In the previous literature, earlier efforts have been made to answer whether globalization is good for consumers, businesses and the welfare of the nations involved. Most of the previous literature has dealt with global markets that consist of the existence of some markets where all firms corresponding to the existing markets compete. This study focuses on the globalization of separated markets into a single market where all firms compete, addressed by Dong and Yuan (2010), Kameda and Ui (2012) and Amir et al. (2017). All these last authors analyzed the effects of globalization, considering a continuous linear demand and the constant marginal cost. Also, they assumed, after globalization, traditional Nash-Cournot conjectures, this is, they assumed that all firms have the same influence on price.

The chapter restricts the attention to the effects on firms' profits caused by the union of separate markets in a globalized single market, considering a discontinuous demand function, quadratic asymmetric costs and under consistent conjectures. The firms in this chapter aim to maximize their profit. Thus they have homogeneous objectives (classic oligopoly).

1.2.2 The Timing of Environmental Tax Policy with a Consumer-Friendly Firm

In this chapter, in the presence of an environmental problem, the effects of the emergence of a consumer-friendly firm when the regulator can or not commit credibly to the ecological tax policy are investigated.

Due to the increasing worldwide trend of incorporating corporate social responsibility (CSR) actions, many industries are characterized by the co-existence of for-profit (profit-maximizer) firms and not-for-profit firms (companies that take into account other aspects besides their benefits in decision-making). Thus, the heterogeneity of objectives among the firms must be considered in the process of policy-making.

Recently, the concept of CSR has become very popular and expanded. Many companies have acquired social awareness. According to the 19th Annual Global CEO Survey (2016), by Pricewaterhouse Cooper, 64% of CEOs claim that "CSR is core to their business rather than being a stand-alone program."

The essence of CSR is that organizations should take into account in their daily operations the society and the external environment; the reason behind this view is that the organization's activities have an impact on them. CSR represents an extensive notion that firms integrate social, economic, or environmental concerns into their values and business operations in a positive manner (Chang et al., 2014). Among all aspects covered by CSR, it draws the attention of researchers in the field of industrial organization to the firms' pro-consumer interests. Consumer-friendly firms do not only aim to maximize their profits but include consumer surplus in their decision-making process as a proxy of their CSR concern.

On the other hand, climate change is a global problem that requires the implementation of effective public policies to counteract it. In the Paris Agreement on climate change, Mexico committed to reducing 22% of its greenhouse gas emissions by 2030. In December 2015, 195 countries adopted the global climate deal. To incentivize emission abatements in contaminating industries, countries' government price pollution through tax systems. For example, the carbon tax which establishes a price on greenhouse gases emissions through a tax rate on the carbon content of fossil fuels. In Mexico, the carbon tax is applied since 2014 to the producers or importers of fossil fuels.

Due to changes in administration or any other political reason, the government cannot always credibly commit itself to a political instrument. In which case, companies have the incentive to strategically plan their investment in abatement, considering the possibility of a subsequent increase in the tax rate by the regulator. This picture was studied previously by Petrakis and Xepapadeas (1999), Poyago-Theotoky and Teerasuwannajak (2002) and Moner-Colonques and Rubio (2015). However, in this chapter, the heterogeneity of the objectives by including a consumer-friendly company in the analysis is taken into account.

1.3 Research Questions

Oligopoly models are investigated in two different settings, the first one is about the profits effect of uniting markets as a single one, and the second is about the implementation of an environmental tax in a problem of time inconsistency. Next, the questions that each investigation pursues to respond are formulated.

1.3.1 Effects of Globalization under Consistent Conjectures

Kameda and Ui (2012) explore a globalized single market through a Nash-Cournot equilibrium model. They study the effects of symmetry on profits and consumer surplus when globalizing monopolies into a single oligopoly market. As in Kameda and Ui (2012), it is used the ratio of the profit obtained after globalization to the profit before globalization to represent the degree of the profit degradation or improvement. However, another solution concept is examined: the model under consistent conjectures, which is described later. This model also differs in that there is a cap price and that the assumption of decreasing returns to scale, instead of constant.

Specifically, next questions are addressed:

- How is the firm's performance regarding profit after the union of the market in contrast with its performance before globalization?
- How cost asymmetry affects the companies' profit ratio after globalization to before globalization? Which firm has a better performance?
- Does complete symmetry denote the strongest coincident profit degradation? How results differ from those obtained under Nash-Cournot conjectures?

1.3.2 The Timing of Environmental Tax Policy with a Consumer-Friendly Firm

Chapter 3 explores the time-inconsistency problem in deciding environmental tax policy in the presence of a consumer-friendly firm. Petrakis and Xepapadeas (1999), Poyago-Theotoky and Teerasuwannajak (2002) and Moner-Colonques and Rubio (2015) examined this problem, but they concentrated on the symmetric case of homogeneous objectives where both firms only maximize their profits under environmental policies. In the model of Chapter 3, the heterogeneity of objectives due to the presence of a consumer-friendly firm is considered. Finally, positive and normative implications are derived.

The following questions are analyzed in this research:

- What is the relationship between the consumer-friendliness and the tax?, how is the tax compared to Pigouvian level?[1]
- How the consumer-friendliness affects environmental damage comparing a committed to a non-committed regime?
- If the regulator is unable to commit credibly, how consumer-friendliness affects social welfare and environmental quality?
- How the timing of government's commitment to the environmental policy affects the resource allocation in this setting?

1.4 Solutions Overview

This dissertation is based on Game Theory. Through the construction of mathematical models, the interaction of agents is represented. The agents (say the companies, or even the government in Chapter 3) are the game's players. Each player has an objective: a for-profit company maximizes its profit, a consumer-friendly company maximizes its profit plus a portion of the consumer surplus, and the government maximizes social welfare. Multi-level games are formulated. The aim is to find the equilibrium of the game under conjectural variations or under the classic Cournot-Nash conjectures. Finally, these solutions are used to make comparisons and analyze the effects of a given policy. The solution concepts used in each chapter are described in more detail below.

1.4.1 Effects of Globalization under Consistent Conjectures

The game consists of two stages: 1) Before globalization each producer satisfies the separated demand of the market that monopolizes, 2) After globalization both firms compete in a globalized single market.

The ratio of the profit obtained after globalization to the profit before globalization is used to represent the degree of the profit degradation or improvement. This way

[1] A tax that is set equal to marginal social cost of the externality.

the effects of uniting separated markets into a single global market are found. For each firm, a ratio larger than the unity represents profit's increase due to globalization; otherwise, there is degradation of the benefits. As in Kameda and Ui (2012), in case of degradation, the largest of the ratios among the producers is a measure of coincident degradation.

Before globalization, there are two separated markets each one with a for-profit maximizer firm that monopolizes the market. Every firm chooses its output to maximize its profit. To solve the maximization problem of each firm we use the well-known Karush-Kuhn-Tucker conditions.

After globalization, the separated markets unite into a single one. Both firms will have to cover the entire market demand. The market's structure is that of a classic duopoly, where the firms choose its output to maximize their profits and the strategy of one player will affect the rival's. Kameda and Ui (2012) approach a similar model, but with constant returns to scale (linear cost) and Nash-Cournot conjectures. Chapter 2's model, instead, considers decreasing returns to scale (quadratic cost) and consistent conjectures.

A.L. Bowley (1924) and Frisch (1933) introduced the concept of conjectural variations in equilibrium (CVE). This type of equilibrium is an alternative solution concept in static games. The behavior of the players is along these lines from Kalashnikov et al. (2014): when each agent picks her most favorable action, it takes into account that every rival's strategy's variation is a conjectured function of her own strategy's variation. This assumption differs from the Nash-Cournot conjectures since with the latter it is assumed that the production of the other company is fixed.

Bulavsky (1997) proposed a new approach. Instead of assuming that each player makes conjectures about the optimal reaction functions of the other players, it is assumed that every player makes conjectures about the change in the market price depending upon infinitesimal variations in its output. The conjectured variations of the price are named *influence coefficients*. Knowing the rivals' influence coefficients, each agent can realize certain *verification procedures* and check out if its influence coefficient is consistent with the others. If all the influence coefficients are mutually consistent, the corresponding equilibrium was called *interior* (or *consistent*) one.

Finally, in Chapter 2, the profit ratios are computed and described. As well, the ratios among the firms and against the resulting ratios under Cournot-Nash conjectures are compared. The classic Cournot model is described in the next subsection.

1.4.2 The Timing of Environmental Tax Policy with a Consumer-Friendly Firm

To analyze the interplay between the strategic choice of abatement technology and the timing of government's commitment to the environmental tax policy, a Cournot duopoly model with a consumer-friendly firm is formulated. It is assumed that both firms invest in abatement technology.

Two alternative policy regimes are considered, each presenting a three-stage game between a welfare-maximizing regulator and firms. This is in order to inspect the properties of either a committed or a non-committed policy regime regarding environmental policy.

The *committed policy regime*:

Stage 1. The regulator sets the emission tax.
Stage 2. The firms, taking the tax rate as given, choose abatement investment simultaneously and independently.
Stage 3. The firms select their production output in a *Cournot* competition game.

The *non-committed policy regime*:

Stage 1. The firms choose abatement investment simultaneously and independently.
Stage 2. The regulator, taking the abatement levels as given, sets the emission tax.
Stage 3. The firms select their production output in a *Cournot* competition game.

Each regime is a bilevel programming problem where the roles of the leader and the follower are reciprocally alternated. On the one hand, in the committed policy game, the government is the leader and the firms are followers. On the other hand, in the non-committed policy regime, both firms are leaders when choosing their abatement strategy and the government behaves as the follower.

In both sequential games, the backward induction, which is a dynamic programming technique, is used as the solution method, starting from the last stage to the first one. In the present model, at the third stage, the Cournot-Nash equilibrium is found.

The Cournot model was introduced in 1838 by the French mathematician, philosopher, and economist A. Cournot, in his book "Researches into the Mathematical Principles of the Theory of Wealth." The original model consisted of a duopoly (two firms), each firm producing a homogeneous good. The total supply would determine the price of the product. Simultaneously, the firms decide their output level. When making its choice each player consider as fixed the output level of the other player (Cournot-Nash conjecture). Thus, knowing that the competitor´s choice will affect its profit, the chosen output by each firm is its "best response" to the rival's choice (Nash equilibrium). The difference with Chapter 3's model is that one of the firms, instead of maximizing its profits, strives to maximize its payoff which is the sum of its profits and a portion of the consumer surplus.

The abatement choice is also a simultaneous game; each firm chooses the abatement investment that maximizes its payoff, the chosen abatement would be its best response to the rival's choice. The tax choice would be chosen by the government to maximize the social welfare.

Finally, the results of the two sequential games are compared. In particular, a comparison of the tax rate of both regimes is presented. Further, I contrast the environmental damage and welfare resulting from each regime.

1.5 Main Contributions

1.5.1 Effects of Globalization under Consistent Conjectures

In this chapter, the effects of merging two separate markets each monopolized initially by a producer into a globalized duopoly market are studied. The study considers a linear inverse demand with cap price and quadratic cost functions. After globalization, the consistent conjectural variations equilibrium (CCVE) of the duopoly game is found. The main contributions are as follow:

By computing the profit ratios, it is described the performance of companies due to the union of the market in contrast with its performance before globalization. Unlike in the Cournot equilibrium, it is shown that a complete symmetry (identical cost functions parameters of both firms) does not imply the strongest coincident profit degradation.

For the situation where both agents are low-marginal cost firms, the company with the technical advantage over her rival has a better ratio of the current and previous profits. Moreover, as the competitor becomes ever weaker, that is, as the slope of the rival's marginal cost function increases, the profit ratio improves.

1.5.2 The Timing of Environmental Tax Policy with a Consumer-Friendly Firm

This study considers the heterogeneity of objectives in a Cournot duopoly model with a consumer-friendly firm. The interplay between the strategic choice of abatement technology and the timing of government's commitment to the environmental tax policy is examined. The principal contributions are:

It is shown that the optimal emission tax under committed policy regime is always higher than that under non-committed one. However, when the consumer-friendliness is high enough, both taxes can be higher than marginal environmental damage. It is also shown that the emergence of a consumer-friendly firm might return better outcomes to both welfare and environmental quality without the commitment to the environmental policy.

1.6 Dissertation Organization

The remainder of this thesis is organized as follows. Chapter 2 displays the study of the effects of globalization under consistent conjectures. A duopoly model with its respective assumptions is formulated, and then the CCVE is found. Next, the profit ratios are determined, which serve to identify the effects of globalization and summarize the results in a series of propositions. Chapter 3 is a study about the time inconsistency problem of an environmental policy in the presence of a consumer-friendly firm. After formulating the model, the equilibrium of the committed sequential game is found. Then it is computed the equilibrium of the non-committed regime, and finally, a comparison of both policy regimes is exhibited. Lastly, concluding remarks are presented, as well as the future research.

Additionally, in the appendix, can be found functions omitted in the main text and the proofs to the propositions. Also, referring to Chapter 3, an extra case is shown in which the consumer-friendly company also has interest in environmental damage.

Chapter 2

Effects of Globalization under Consistent Conjectures[2]

Published article in ***International Journal of Combinatorial Optimization Problems and Informatics***

By Mariel A. Leal-Coronado, Arturo García-Martínez, and Viacheslav V. Kalashnikov

2.1 Introduction

The purpose of the present paper is to investigate a market with two competing producers of an identical commodity. We consider two stages: before globalization (separate markets) and after globalization (united market). Before globalization, each producer satisfies the separate demand of the market that it monopolizes. After globalization, both firms compete in a united market. This model is often said to have the structure of a pure (classic) duopoly where both companies satisfy the complete market demand.

One can find numerous studies on the effects of combining two or more markets in the literature. According to Kameda and Ui (2012), there are two types of global markets: a) the free trade market which allows the existence of n different markets with a separate supplier; and b) a single integrated market in which all producers compete.

Since the 1980s, there has been a lot of research on the role of imperfect competition. This was pointed out in Brander and Spencer (2015), which deals with global markets of type a). In fact, there are several works which models correspond to these type of markets. Some examples are found in Brander (1981), Brander and Krugman (1983) and Yilmazkuday and Yilmazkuday (2014), too. On the other hand, Kameda and Ui (2012) analyze a globalized market of type b), through a Nash-Cournot equilibrium model, whereas in Kameda and Ui (2012), the authors examine cases where all producers' profits are degraded in the same manner. For each producer, they use the ratio of the profit obtained after globalization to the profit before globalization to represent the degree of the profit degradation, and the largest of the ratios among the producers is a measure of coincident degradation. They found that under a complete symmetry, i.e. when the values of parameters of cost and demand functions are equal, all producers have profit degradation coincidently. For the model they use which boasts linear demand functions for the separated markets and the globalized market, as well as linear cost functions, under Nash-Cournot conjectures, the value of the measure of coincident degradation is the lowest (the worst) when the firms are identical.

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The present Chapter also discusses a situation of type b). As in Kameda and Ui (2012), we use the ratio of the profit obtained after globalization to the profit before globalization to represent the degree of the profit degradation or improvement. However, our purpose is to analyze the effects of globalization considering the diverse values that can take the parameters of the cost functions of the companies, which in our case are quadratic. We reveal that is possible that one producer loses while the other one gains; or both lose.

As well, at the stage of globalization, when competition takes place, we raise a kind of equilibrium with consistent conjectural variations (CCVE). Conjectural Variations Equilibria (CVE) was introduced by Bowley (1924), and Frisch (1933) as another possible solution concept in static games. According to this concept, agents behave as follows as was stated in Kalashnikov et al. (2011): each agent chooses her most favorable action taking into account that every rival's strategy is a conjectured function of her own strategy. In Kalashnikov et al. (2011) and Kalashnykova et al. (2012), we studied mixed oligopoly models with consistent conjectural variations (CCV), which correspond to the market price variations due to the change in the output level of a producer. Concepts such as exterior and interior equilibrium were introduced, and proofs of existence and uniqueness of equilibrium were presented in the above-mentioned papers. We apply these concepts in our present paper, too.

The Chapter is organized by follows. In Section 2.2, we describe the mathematical model and specify the assumptions to accept for each stage. This section shows the optimal output levels produced by each firm before globalization as well and finds the consistent conjectural variations equilibrium price and production volumes. In Section 2.3, we define two types of agents: low-marginal and high-marginal cost firms. As we study a market with 2 agents, we have four feasible situations corresponding to the possible combination of types of firms. We define the profit ratio and compute it for each situation in terms of the parameters in order to analyze the effect of the cost parameters on this ratio. To do so we use the concept of technical advantage introduced by Flores and García (2016). In this section, we also display an example which shows that unlike the Nash-Cournot case Kameda and Ui (2012), a complete symmetry does not necessarily render the worst-case ratio under consistent conjectures. Finally, in Section 2.4, we present our conclusions and outline our future work.

2.2 Model Specification

Before globalization, consider two monopolistic markets. Each monopoly faces an active demand $D_i, i\epsilon\{0,1\}$ which does not depend on market price and a passive demand $G_i(p_i)$ whose argument p_i is the market clearing price. We will assume that in every market the price value $p_i = \bar{P}$ is the cap price. This means that the demand functions have a discontinuity point (a break) and for prices higher than $\bar{P}$

the demand is zero. Therefore, the company i output volume $q_i \geq 0$, will satisfy the following inequality if the market is “balanced”:

$$g_i(p_i) + D_i \leq q_i \leq G_i(p_i) + D_i . \quad (2.1)$$

Here, $g_i(p_i)$, is the right limit of the function Gi at any point while the left limit of this function at each point is assumed to coincide with its proper value.

After globalization, both firms compete in a globalized market. The consumers' (passive) demand is described by a demand function $G(p_w)$, whose argument pw is the market clearing price. An active demand value D is non-negative and does not depend on the market price. Here we take for granted that after globalization, the cap price will be the same as before globalization. Since the demand function has a point of discontinuity (a break at the cap price $\bar{P}$), the balance between the demand and supply for a given price p_w is described by the following (“balance”) inequality:

$$g(pw) + D \leq Q \leq G(pw) + D . \quad (2.2)$$

Here, $g(p_w)$ is the right limit of the function G at any point p_w and $Q = q_0 + q_1$.

2.2.1 Assumptions

Accept the following assumptions about the demand and cost functions in order to study the effects of globalization.

Before Globalization

A1.1.The inverse demand function for each firm $\boldsymbol{i}, \boldsymbol{i} \in \{\mathbf{0}, \mathbf{1}\}$, is defined as follows:

$$p_i(\theta_i) = \begin{cases} \overline{P} & if\ 0 \leq \theta_i \leq \bar{Q}/2\,; \\ c - d\theta_i & if\ \bar{Q}/2 < \theta_i \leq c/d\,. \end{cases} \quad (2.3)$$

Here c and d are positive values, and $\overline{P} = c - d\bar{Q}/2$. The total quantity demanded in the market i at the price pi is θ_i, which includes the passive and the active quantities demanded.

A1.2. For each $i \in \{0, 1\}$, the cost function $f_i(q_i)$ is quadratic, i.e., $f_i(q_i) = \frac{1}{2} a_i q_i^2 + bq_i$ where $a_i > 0$ and $0 < b < c$.

A1.3. $\overline{P} > max_{i \in \{0,1\}}\{a_i\overline{Q}/2 + b\}$.

After Globalization

A2.1.The market inverse demand function is defined as follows:

$$p_w(\theta) = \begin{cases} \overline{P} & if\ 0 \le \theta \le \overline{Q}; \\ c - d\theta/2 & if\ \overline{Q} < \theta \le 2c/d\,. \end{cases} \quad (2.4)$$

Here $c, d,$ and $\overline{P}$ are defined as in A1.1. The variable θ is the total quantity demanded (including the passive and the active demand).

Assumption A1.2 about the cost function is also made; the cost structure won't change after globalization. As a consequence of A1.3, if $q_0 + q_1 < \overline{Q}$ then $\overline{P} > a_i q_i + b$, for at least one $i, i \in \{0, 1\}$.

2.2 Objective Functions of the Companies

2.2.1. Before Globalization

Recall that before globalization exists a single company in each market commercializing the commodity. Company i, ($i \in \{0,1\}$) chooses its output volume so as to maximize its net profit function: $\pi_i(q_i) = p_i(q_i)q_i - f_i(q_i)$.

Note that assumption A1.3 implies that the output value that maximizes the benefits cannot be less than $\bar{Q}/2$. Because of that, we can rewrite the maximization problem of any firm with sub-index i as follows:

$$\begin{aligned} &\underset{q_i}{\text{maximize}} && \pi_i(q_i) = p_i(q_i)q_i - f_i(q_i), \\ &\text{subject to} && q_i \ge \overline{Q}/2, \end{aligned} \quad (2.5)$$

which can be easily solved by Karush-Kuhn-Tucker (KKT) equations. The optimal output value $\bar{q}_i$ for private firm $i, i \in \{0, 1\}$ is found as:

$$\bar{q}_i = \begin{cases} \dfrac{c-b}{2d+a_i} & if\ \dfrac{c-b}{2d+a_i} > \dfrac{\overline{Q}}{2}; \\ \dfrac{\overline{Q}}{2} & if\ \dfrac{c-b}{2d+a_i} \le \dfrac{\overline{Q}}{2}. \end{cases} \quad (2.6)$$

2.2.2. After Globalization

After globalization, there is an integrated market where both companies compete in a classic duopoly. The price at this stage is determined in the global market, so it obeys the inverse demand function (2.4) cited in assumption A2.1.

The problem of each private company $\boldsymbol{i}$ is to maximize its net profit

$$\xi_i(q_i) = p_w\,(Q)q_i - f_i(q_i), i = 0{,}1\ . \quad (2.7)$$

The output level of each company under the assumptions made is found using the theory of Kalashnikov et al. (2014). As in Kalashnikov et al. (2014), we also claim that the output volume chosen by a producer influences the market price. This can be described by a conjectured function of the variations of the price upon variations of the production volume. Then, the first order maximum condition to define the equilibrium would have the form $i, i \in \{0, 1\}$:

$$\frac{\partial \xi_i}{\partial q_i} = p_w(Q) + \frac{\partial p_w(Q)}{\partial q_i} \cdot q_i - a_i q_i - b \begin{cases} = 0 & if\ q_i > 0; \\ \leq 0 & if\ q_i = 0. \end{cases} \tag{2.8}$$

As in Kalashnikov et al. (2014), denote $v_i = -\partial p_w(Q)/\partial q_i$. In order to describe each agent's behavior, we need to evaluate v_i. The conjectured dependence of p_w on q_i must account for the (local) concavity of the i –th agent's objective function; otherwise one cannot guarantee that the output volumes found via the *first order optimality conditions* (2.8) *maximize* (but not minimize) the profit functions. For instance, it suffices to assume that the coefficient v_i (from now on referred to as the i –th agent's *influence coefficient*) is nonnegative and constant, for $i, i \in \{0, 1\}$.

In Kalashnikov et al. (2014) and Kalashnykova et al. (2011), we defined the concept of *exterior equilibrium*, i.e., *conjectural variations equilibrium* (CVE) with the influence coefficients fixed in an exogenous way. As the competition after globalization has been represented by the model presented in Kalashnikov et al. (2014), the equilibrium would be found as in the mentioned publication. Theorem 1 in Kalashnikov et al. (2014) establishes the existence and unicity of the exterior equilibrium $(p_w\,;\ \tilde{q}_0, \tilde{q}_1)$ under assumptions A1.2 and A2.1, and also provides the left and right derivatives of the equilibrium price $p_w = p_w(D, v_0, v_1)$ with respect to D. This theorem serves as a base for the concept of *interior equilibrium*, which was defined in Kalashnikov et al. (2014) as the exterior equilibrium with *consistent* conjectures (influence coefficients). Under the above assumptions, according to Theorem 2 in Kalashnikov et al. (2014), there exists *interior equilibrium* after globalization.

Consistent Conjectural Variations Equilibrium:

Let $\tau = \begin{cases} -\infty & if\ p_w = \bar{P}, \\ -2/d & otherwise. \end{cases}$

Given the previous results obtained in Kalashnikov et al. (2014) the influence coefficient of the agent $i, i \in \{0, 1\}$, after globalization is:

$$v_i = \frac{1}{\frac{1}{v_{-i} + a_{-i}} - \tau}\ , i = 0, 1 \tag{2.9}$$

where the symbol $-\boldsymbol{i}$ represents the competitor's sub-index.

In (2.9), $\tau \in [-\infty, 0]$. When $\tau = -\infty$, system (2.9) has the unique solution $v_i = 0, i \in \{0, 1\}$. The latter result corresponds to the perfect competition equilibrium (*cf*., Kalashnikov et al. (2014)).

The following result was already derived and published as Theorem 3 in Kalashnikov et al. (2014) and Theorem 4.3 in Kalashnykova et al. (2011), including for the case of a mixed oligopoly (competition among a public firm and several private companies).

Theorem 2.1 (Kalashnikov et al. (2014)-Kalashnykova et al. (2011)). *Under assumptions A1.2 and A2.1, for any* $\tau \geq 0$*, Eq.* (2.9) *has a unique solution* $vi = vi(\tau), i \in \{0, 1\}$*, continuously depending upon* τ*. Furthermore,* $vi(\tau) \to 0$ *when* $\tau \to -\infty$*, and strictly increases and tends up to* $vi(\tau)$ *as* $\tau \to 0, i = 0, 1$*.*

Therefore, the solution of the system formed by equations (2.9) for the firm *i* influence coefficient is:

$$v_i = \begin{cases} \frac{-a_i}{2} + \sqrt{\frac{{a_i}^2}{4} + \frac{\Gamma}{K_{-i}}}, & \tau = -\frac{2}{d}; \\ 0, & \tau = -\infty, \end{cases} \tag{2.10}$$

i = 0,1, where $\Gamma = a_i + a_{-i} + 2a_i a_{-i}/d$ *and* $K_{-i} = 2\left(2 + \frac{2}{d} a_{-i}\right)/d$.

For the interior equilibrium price $p_w > b$, Theorems 1 and 2 in Kalashnikov et al. (2014) imply that relationship (8) defines uniquely the equilibrium production volumes $\tilde{q}_i, i \in \{0, 1\}$, taking into account that $p_w = \bar{P}$ implies $v_i = 0$:

$$\tilde{q}_i = \begin{cases} \frac{p_w - b_i}{v_i + a_i}, & p_w < \bar{P}; \\ \frac{p_w - b_i}{a_i}, & p_w = \bar{P}, \end{cases} \tag{2.11}$$

i = 0,1. However, assumption A1.3 entails that the total output level given by (2.11) at $p_w = \bar{P}$, is greater than $\bar{Q}$, but at this price the quantity demanded is at most $\bar{Q}$, which means that the market is *not* balanced. Hence, the equilibrium can be reached only when $p_w < \bar{P}$.

In the equilibrium when $p_w < \bar{P}$, the total supply output equals the demand in the market. Then, from A2.1, $p_w = c - dQ/2$, where $Q = \tilde{q}_0 + \tilde{q}_1$. Plug in this in the equilibrium outputs (2.11) to obtain the total output and the equilibrium price p_w. These values can be found in Appendix A.1

2.3 Effects of Globalization on Profits

To find the effects of globalization on profits we look for the ratio of benefits. We determine conditions involving the parameters under which these ratios are greater or smaller than 1. If the profit ratio is greater than 1 for company $i, i \in \{0,1\}$ we say that globalization is beneficial for this firm, and it is *not* otherwise, that it, if the profit ratio is less than 1. In order to do that, we first introduce the properties of companies being *low-marginal*, or vice versa, *high-marginal* cost firms.

Definition 2.1. We say that agent i is a *low-marginal cost firm* (*LMCF*) if the marginal cost $f'_i(q_i)$ evaluated at $\bar{Q}/2$ is less than the cap price minus a proportion d of the quantity $\bar{Q}/2$, that is, $f'_i(\bar{Q}/2) < \bar{P} - d\,\bar{Q}/2$. Conversely, agent i is a *high-marginal cost firm* (*HMCF*) if $f'_i(\bar{Q}/2) \geq \bar{P} - d\,\bar{Q}/2$.

Before globalization, the output level produced by firm $\boldsymbol{i}$ to supply to a separate market depends on the value of the corresponding parameters. On the one hand, if firm i is an *LMCF*, it produces $\bar{q}_i = \frac{c-b}{2d+a_i}$. On the other hand, if it is an *HMCF* it supplies $\bar{q}_i = \frac{\bar{Q}}{2}$. Because of that, before globalization, four situations in total are feasible depending on the characteristics of the firms of both markets. These situations are described in Table 2.1, which shows the optimal outputs and the profits for both firms.

Table 2.1 Possible Situations.

	Before Globalization		
Sit.	Type of firms	Outputs: $\bar{q}_i$, $i \in \{0,1\}$	Profits: $\pi_i(\bar{q}_i)$, $i \in \{0,1\}$
1	Both are LMCF	$\bar{q}_0 = \frac{c-b}{2d+a_0}, \bar{q}_1 = \frac{c-b}{2d+a_1}$	$\pi_0(\bar{q}_0) = \frac{(c-b)^2}{2(2d+a_0)}, \pi_1(\bar{q}_1) = \frac{(c-b)^2}{2(2d+a_1)}$
2	Agent 0 is an LMCF and agent 1 is an HMCF	$\bar{q}_0 = \frac{c-b}{2d+a_0}, \bar{q}_1 = \frac{\bar{Q}}{2}$	$\pi_0(\bar{q}_0) = \frac{(c-b)^2}{2(2d+a_0)}, \pi_1(\bar{q}_1) = \frac{1}{8}\bar{Q}\big(4(c-b) - \bar{Q}(2d+a_1)\big)$
3	Agent 0 is an HMCF and agent 1 is an LMCF	$\bar{q}_0 = \frac{\bar{Q}}{2}, \bar{q}_1 = \frac{c-b}{2d+a_1}$	$\pi_0(\bar{q}_0) = \frac{1}{8}\bar{Q}\big(4(c-b) - \bar{Q}(2d+a_0)\big), \pi_1(\bar{q}_1) = \frac{(c-b)^2}{2(2d+a_1)}$
4	Both are HMCF	$\bar{q}_0 = \frac{\bar{Q}}{2}, \bar{q}_1 = \frac{\bar{Q}}{2}$	$\pi_i(\bar{q}_i) = \frac{1}{8}\bar{Q}\big(4(c-b) - \bar{Q}(2d+a_i)\big), i \in \{0,1\}$

Let R_i denote the profit ratio of company $i, i \in \{0,1\}$ and be given by:

$$R_i = \frac{\xi_i(\tilde{q}_i)}{\pi_i(\bar{q}_i)}\,. \tag{2.12}$$

Formula (2.12) would take different values according to the faced situation.

2.3.1 The Measure of Coincident Profit Degradation

Globalization may improve or degrade the profits of the companies. However, Kameda and Ui (2012) study the cases when coincident profit degradation occurs, that is, both firms have smaller profits after globalization than before. In the above-mentioned work, the profit ratio of a producer after globalization to that before globalization is proposed as the degree of profit degradation for the producer due to globalization. They utilize the largest of the ratios of profit degradation among producers as a measure of *coincident degradation*. According to Kameda and Ui (2012), the reason is: a smaller value of the measure is supposed to indicate stronger coincident degradation. The situation where only one of the producers suffers profit degradation cannot be considered overall coincident producer profit degradation as far as the other producer enjoys profit improvement. The measure of coincident profit degradation used in Kameda and Ui (2012) for a duopoly is defined by the following equality:

$$k^R = max\{R_0, R_1\}. \tag{2.13}$$

The main result obtained in Kameda and Ui (2012) is that the worst-case ratio of coincident profit degradation for all producers due to globalization is reached by a market system if, and only if the system is in a complete *symmetry*. In the next subsection, we show how this result is not necessarily true in the case of the equilibrium with consistent conjectural variations, at least for a system of two firms with quadratic cost functions. We also describe the effect of the cost parameters values, a_i and a_{-i} on the profit ratios. In order to do so, we use the concept of *technical advantage*. According to the definition of technical advantage introduced in Flores and García (2016), a firm has a technical advantage over its rival, if it can produce the same output that its rival produces at lower marginal and total costs than its rival. We say that firm i has a technical advantage over firm $(-i)$ if a_i < a_{-i}.

The proofs of all propositions are found in Appendix A.2-A.4.

2.3.2 Situation 1

Situation 1 stated in Table 2.1 refers to the case when both agents are low-marginal cost firms. Substitute the profits at the equilibrium [3] and the optimal profits (Table 2.1) into formula (2.12), and after some algebraic manipulations obtain:

$$R_i = \frac{2d + a_i}{2v_i + a_i}\left(\frac{2}{d}v_i\right)^2, \tag{2.14}$$

where $\boldsymbol{v_i} = \frac{-a_i}{2} + \sqrt{\frac{{a_i}^2}{4} + \frac{\Gamma}{K_{-i}}}$ according to equation (2.10).

[3] See Appendix A.1

Proposition 2.1. *The profits of private firm I suffer degradation if, and only if*

$$\lambda_1(a_i, a_{-i}, d) + \lambda_2(a_i, a_{-i}, d) > 1, \tag{2.15}$$

where $\lambda_1(a_i, a_{-i}, d), \lambda_2(a_i, a_{-i}, d) \in (0,1)$ *are continuous functions specified in Appendix A.1.*

Coincident degradation of the benefits occurs when inequality (2.15) is satisfied for both $i = 0, 1$. The degradation or increase of company *i*'s profit depends not only on the cost parameters of the same company but also on the cost parameters of the other agent.

Proposition 2.2. *The profit ratio of competitor* i *increases if* a_{-i} grows.

Proposition 2.2 states that the larger the coefficient of the quadratic term of the rival's cost function, the lower the profit degradation for producer i (or, its profits may even increase). The proof of Proposition 2.2 shows that the increase of the parameter a_{-i} of the cost function of the rival affects positively the profit ratio of player i, as expected. However, the parameter a_i of its own cost function has an ambiguous effect on this ratio. In order to show that, calculate the derivative of R_i with respect to a_i

$$\frac{\partial R_i}{\partial a_i} = \frac{v_i}{d^2(d + a_{-i})(2v_i + a_i)^3} \chi_i(a_i, a_{-i}, d)\,, \tag{2.16}$$

where $\chi_i(a_i, a_{-i}, d)$ is a continuous function specified in *Appendix A.1*. The sign of this derivative is the same as the sign of $\chi_i(a_i, a_{-i}, d)$. In order to describe the behaviour of $\chi_i(a_i, a_{-i}, d)$, let $a_i = \sigma a_{-i}$ and $d = \rho a_{-i}$; $\sigma, \rho > 0$. By substituting them in χ_i, we have: $\chi_i(\rho, \sigma, a_{-i}) = a_{-i}^4 \tilde{\chi}_i(\rho, \sigma)$, where $\tilde{\chi}_i(\rho, \sigma)$ is a continuous function of two variables specified in *Appendix A.1*.

In general, the sign of $\tilde{\chi}_i$ depends on both values ρ and σ. However, in particular, we can say that $\tilde{\chi}_i$ shows various types of behavior when ρ takes values around zero, however $\tilde{\chi}_i \to 0$ when $\rho \to 0$. While ρ is cut off from zero, that is, if $\rho \geq \bar{\rho}_1 > 0$, then $\tilde{\chi}_i$ takes negative values, for any value of $\sigma > 0$. That is, a little increments in a_i affect negatively the profit ratio R_i, regardless of whether firm i has a technical advantage over her rival or not, while the value of d doesn't exceed $\bar{\rho}_1$ times a_{-i} (in this case, d may also be less than a_{-i}, but remember that the behavior of $\tilde{\chi}_i$ is ambiguous when ρ is very close to zero). If $\sigma \leq 1$, which means that the rival firm $(-i)$ has no technical advantage over firm i, the effect of little increments in a_i is positive when $\rho < \bar{\rho}_2$. This happens if d is large enough as compared to a_{-i}.

For the current situation, the profits of the weaker firm $(-\boldsymbol{i})$ are degraded after globalization. Another important fact is that if a firm has a technical advantage over the other, the degradation of her own profit due to globalization (if the latter happens at all) is lower than the profit degradation of the other firm. Even more, the profits of firm i can increase. These results are summarized in Proposition 2.3.

Proposition 2.3. *If $a_i < a_{-i}$, i.e., competitor i has a technical advantage over $(-i)$, then*

a) $R_{-i} < 1$;

b) $R_{-i} < R_i$.

Note that if we consider the case where there is coincident degradation of the profits, the measure of the latter in this case would equal $K^R = R_i$, i.e., the profit degradation of the firm with the technical advantage.

Under the complete symmetry, both producers suffer coincident profit degradation. This result is the same as in Brander and Spencer (2015) and is stated in Proposition 2.4:

Proposition 2.4. *If the firms are symmetric ($a_i = a_{-i} = a$) the ratio of both firms is given by*

$$R = \frac{2d + a}{2\sqrt{\frac{a^2}{4} + \frac{ad}{2}}} \left(\frac{a}{\frac{a}{2} + \sqrt{\frac{a^2}{4} + \frac{ad}{2}}} \right)^2 . \qquad (2.17)$$

This resulting value is less than 1 for any positive values of a and d, which means that globalization degrades profits for each company when both firms face the same costs.

In contrast to Kameda and Ui (2012), the latter is *not* necessarily the worst case under consistent conjectures. We introduce a numerical example to show it. In the following examples, we compute, together with the consistent conjectural variations equilibrium (CCVE), the equilibrium under Nash-Cournot conjectures considering the quadratic cost functions. In Kameda and Ui (2012), the cost function is linear. Nevertheless, our examples with quadratic costs show that a complete symmetry implies the worst-case ratio under Nash-Cournot conjectures, too.

Example 2.1. Consider a duopoly with $c = 50, d = 10, \bar{P} = 30, \bar{Q} = 4, b = 1,$ and $a_0 = 0.1$. Table 2.2 simulates Situation 1 for the above-given values of the parameters and different values of the parameter a_1, starting with $a_1 = 0.06$ and increasing with a mesh of 0.02. The above-mentioned table shows the influence coefficients in the case of CCVE, while the values of the influence coefficients at the Nash-Cournot equilibrium are always $v_0 = v_1 = -d/2$. The minimal value of the measure k^R among the values presented in Table 2.2 is achieved when $a_1 = 0.06$, $k_{CV}^R = 0.23021$, which means that the worst case is not the one where the firms are symmetric, unlike the Nash-Cournot case in which the worst case ratio is obtained when $a_1 = a_0 = 0.1$. In the CCVE, as long as firm 1 has a technical advantage over firm 0, $k_{CV}^R = 0.23021$ (when $a_1 = a_0$, $k_{CV}^R = R_1 = R_0$).

With regard to R_1, notice that $\rho = \frac{10}{0.1} = 100 > \overline{\rho}_2$. Therefore, at least when firm 0 has no technical advantage over firm 1 ($\sigma \leq 1$), R_1 will increase along with a_1. This explains why a complete symmetry does not necessarily entail the worst case ratio in for conjectural CVEs.

Table 2.2 Example 2.1: $c = 50, d = 10, \bar{P} = 30, \bar{Q} = 4, b = 1$ and $a_0 = 0.1$

a_1	v_0	v_1	R_0^{CV}	R_1^{CV}	k_{CV}^R	R_0^C	R_1^C	k_C^R
0.06	0.58490	0.60238	0.21661	0.23021	**0.23021**	0.88571	0.89442	0.89442
0.08	0.62298	0.63164	0.23183	0.23856	0.23856	0.88804	0.89238	0.89238
0.10	0.65887	0.65887	0.24618	0.24618	0.24618	0.89036	0.89036	**0.89036**
0.12	0.69290	0.68438	0.25980	0.25319	0.25980	0.89266	0.88834	0.89266
0.14	0.72532	0.70839	0.27277	0.25968	0.27277	0.89496	0.88634	0.89496

However, in Example 2.2 shown in Table 2.3 where $c = 50, d = 0.1, \bar{P} = 49.8, \bar{Q} = 4, b = 1$, and $a_0 = 0.1$, the profit ratio of firm 1 decreases as it loses the technical advantage and becomes weaker ($\rho = \frac{0.1}{0.1} = 1$), whereas the profit ratio of firm 0 increases as a_1 grows. In this case, the worst measure occurs when the firms are symmetric.

Table 2.3 Example 2.2: $c = 50, d = 0.1, \bar{P} = 49.8, \bar{Q} = 4, b = 1$ and $a_0 = 0.1$

a_1	v_0	v_1	R_0^{CV}	R_1^{CV}	k_{CV}^R	R_0^C	R_1^C	k_C^R
0.06	0.03292	0.03633	0.78401	1.03483	1.03483	0.83424	1.07555	1.07555
0.08	0.03498	0.03649	0.86406	0.97464	0.97464	0.90354	1.01047	1.01047
0.10	0.03660	0.03660	0.92820	0.92820	**0.92820**	0.96000	0.96000	**0.96000**
0.12	0.03790	0.03670	0.98068	0.89125	0.98068	1.00682	0.91973	1.00682
0.14	0.03898	0.03677	1.02439	0.86112	1.02439	1.04625	0.88685	1.04625

2.3.2 Situations 2 and 3

In Situation 2 from Table 2.1, there is one *low-marginal cost* firm and the rival is a *high-marginal cost* company. Plug in the equilibrium and optimal values into formula (2.12), and simple algebraic manipulations yield (in Situation 3, the results are similar):

$$R_0 = \frac{2d + a_0}{2v_0 + a_0}\left(\frac{2}{d}v_0\right)^2, \qquad R_1 = \frac{\frac{1}{2(2v_1 + a_1)}((c-b)\frac{2}{d}v_1)^2}{\frac{\bar{Q}}{2}(2d + a_1)\left(\frac{c-b}{2d + a_1} - \frac{1}{2}\frac{\bar{Q}}{2}\right)}. \tag{2.18}$$

Here, Propositions 2.1 and 2.2 are still valid for firm 0 because the formulas of the profit ratio for firm 0 from equations (2.18) are identical to formulas (2.14). Firm 0 would face degradations of her profits if, and only if (2.15) holds. The profit ratio of firm 0 increases with respect to a_1. The larger the value of a_1 the higher is the profit ratio for firm 0. The latter means that if globalization damages the profits of firm 0, the degradation would not be too strong as it would be with a smaller value of a_1. For firm 1, the higher values of the slope of the rival's marginal cost would result in a better profit ratio as stated in Proposition 2.5.

Proposition 2.5. *Profit ratio of competitor* 1 *increases with respect to* a_0*.*

2.3.3 Situation 4

In Situation 4 from Table 2.1, both producers are high-marginal cost firms. Substituting the equilibrium and optimal values in formula (2.12), after simple algebraic manipulations one obtains for $i = 0, 1$:

$$R_i = \frac{\frac{1}{2(2v_i + a_i)}((c-b)\frac{2}{d}v_i)^2}{\frac{\overline{Q}}{2}(2d + a_i)(\frac{c-b}{2d+a_i} - \frac{1}{2}\frac{\overline{Q}}{2})} \qquad (2.19)$$

Proposition 2.6. *The profit of competitor i increases together with* a_{-i}*.*

Therefore, the effect of the increase of the quadratic cost coefficient a_{-i} on the rival's profit (player i) is positive.

2.4 Main Findings and Future Work

In this Chapter, we examine consistent conjectural variations equilibrium (CCVE) for a duopoly in a market of a homogeneous product. We study the effects of uniting two separate markets each monopolized by a producer: after globalization, both firms compete in one common market. Our model assumes an inverse demand function with a cap price and quadratic cost functions of both agents. Similar to previous studies, we investigate if the companies lose or gain due to globalization by evaluating their profit ratios, i.e., the ratios of their net profits after and before entering the common market. For the situations where both agents are low-marginal cost firms, we find that the company with a technical advantage over her rival has a better profit ratio. In addition, as the rival becomes weaker, this is, as the slope of the rival's marginal cost function increases, the agent's profit ratio enhances, too. Moreover, when both agents are low-marginal cost firms, at least the weaker company suffers degradation of her profits due to the globalization.

Unlike the previous study, Kameda and Ui (2012), which considers Nash-Cournot equilibrium, we show with an example that the complete symmetry of the agents does *not* always provide the worst case (the lowest profit ratio) in the case of CCVE. As a consequence, we demonstrate that under consistent conjectures it is important to analyze not only the case where firms are symmetrical, although this leads us to deal with more complicated or even intractable problems.

In our forthcoming papers, we are going to analyze a system with a public firm whose maximized objective is distinct from its net profit.

Chapter 3

The Timing of Environmental Tax Policy with a Consumer-Friendly Firm[4]

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3.1 Introduction

Recently, a large number of companies participated in fair trade or greenhouse gas reduction programs and issued various statements on corporate social responsibility (CSR) and outlined activities in their annual reports.[5] Due to the current expansion of CSR, many industries are characterized by the co-existence of for-profit firms and not-for-profit firms. Thus, the heterogeneity of objectives among the firms emerges as an essential research topic in the literature.[6]

Numerous theoretical studies have formulated models for analyzing the CSR activities in different competition models.[7] In the fields of public economics and industrial organization, many studies considered an oligopoly model where profit-maximizing firms compete with their rival firms that adopt CSR activities. In particular, as one way of adopting CSR initiatives, they utilized consumer surplus as a proxy of CSR concern and define the objective of the firm as a combination of consumers surplus and its profits. Then, the firms put a higher weight on output in an oligopoly, which induces rivals to reduce their output and thus profits can be higher for a firm which adopts CSR activities.[8] Thus, the firm may strategically use CSR initiative as a commitment to expand the outputs and thus the firm that adopts CSR obtains higher profits than its profit-seeking competitors and induces a higher level of social welfare. However, these results put aside the environmental policy, which is becoming an essential part of contemporary economies. As pointed out Lambertini and Tampieri (2015) and Garcia et al. (2018), in the presence of an environmental problem, firms concern on CSR (and thus committing a higher output) might be neither profitable to the firms nor desirable to the society.

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[5] See CSR trend report by PricewaterhouseCoopers (2010) and KPMG (2013, 2015).

[6] For example, Chirco et al. (2013), Matsumura and Ogawa (2014), Flores and Garcia (2016) and Cho and Lee (2017) showed that behavioral heterogeneity may produce different market structure.

[7] In the CSR literature, see Goering (2012, 2014), Kopel and Brand (2012), Brand and Grothe (2013, 2015), Nakamura (2014), Chang et al. (2014), Kopel (2015) and Matsumura and Ogawa (2014, 2017) among others.

[8] The approach that CSR concerns account for consumer surplus is very closely related to the literature on strategic delegation and sales targets for managers in oligopolies, as suggested by Fershtman and Judd (1987) and Vickers (1985).

In the process of policy-making, on the other hand, the ability of a government to commit credibly to an environmental policy has significant implications to support the superior welfare properties associated with a committed policy. Due to the political reason, however, if the regulator cannot commit credibly to the stringency of the policy instrument, firms have strategic incentives because the regulator has an ex-post possibility to ratchet up regulation.[9] Petrakis and Xepapadeas (1999), Poyago-Theotoky and Teerasuwannajak (2002) and Moner-Colonques and Rubio (2015) examined environmental taxation under the time inconsistency problem when the regulator is not able to commit credibly and showed an interesting result that firms undertake increased abatement activities generating less pollution, which might result in higher welfare. However, they concentrated on the symmetric case of homogeneous objectives where both firms only maximize their profits under environmental policies. However, asymmetric equilibrium can produce the same incentive to ratchet down the regulation and increase profits and welfare under efficient abatement technology. In the present paper, we complement and elucidate these works by examining the role of CSR that can play in designing of environmental policy under asymmetric equilibrium.

In this Chapter, we consider a quantity-setting Cournot duopoly model with heterogeneous objectives between firms where a consumer-friendly firm competes with a for-profit firm emitting pollutants in the presence of emission tax.[10] We then analyze the interplay between the strategic choice of abatement technology and the timing of government's commitment to the environmental policy. In specific, we consider the ability of the environmental regulator to commit credibly or not to an emission tax, and examine the properties of either committed or non-committed regime regarding environmental policy. In the former case of the *committed policy regime*, the regulator sets the emission tax then the firms, taking the tax rate as given, choose abatement investment. In the latter case of the *non-committed policy regime*, firms first select their abatement levels and then the regulator sets the emission tax. Thus, under the non-committed policy regime, when an emission tax is chosen firms would expect the regulator to change it after they have determined their investment in abatement. We investigate this time-inconsistency problem in deciding environmental policy in the presence of a consumer-friendly firm.

The main findings we obtain are as follows: Regarding positive implications on emission taxes, we show that the tax rate under the committed policy regime is always higher than that under the non-committed one, but both emission taxes can be higher than marginal environmental damage when the consumer-friendliness is high enough. It represents that the strategic incentive of innovation will ratchet down the regulator's ex-post possibility to decide tax rate, which is dependent on the strategic relationship between the firms. In particular, as the concern on consumer surplus rises, a consumer-friendly firm produces more outputs

[9] See, for example, Gersbach and Glazer (1999), Requate and Unold (2003) and D'Amato and Dijkstra (2015) for a commitment issue regarding environmental regulation.

[10] Similar market configuration can be found in the literature on mixed oligopolies where the objectives between public and private firms differ. Recent works on mixed markets with environmental tax policies can be found in Wang and Wang (2009), Pal and Saha (2014), Pal and Saha (2015), Xu et al. (2016), Kim et al. (2017) and Lee and Xu (2017) among others.

aggressively, which increases total outputs and total emissions even under higher abatement levels. Thus, irrespective of policy regimes, the optimal emission tax will be higher than Pigouvian level. This sharply contrasts to the previous result in the private market where firms have homogeneous payoffs under environmental taxation. For example, Shaffer (1995) and Lee (1999) showed that the optimal emission tax should be lower than marginal environmental damage under oligopolistic competition.[11]

Regarding normative implications on the two policy regimes, we also show that the non-committed policy regime can induce the firms to decide not only more outputs and higher profits but also more abatement and lower emission than under the commitment when the consumer-friendliness is high and the efficiency of abatement technology is not so high. Therefore, a consumer-friendly firm under the non-committed policy regime might yield better outcomes to the welfare and environmental quality as well. It implies that the heterogeneity of objectives between the firms is significant in designing of environmental policies.[12]

The remainder of this Chapter is organized as follows. In Section 3.2, we formulate a Cournot duopoly model with a consumer-friendly firm having abatement technology. We analyze the committed and non-committed policy regimes, 3.respectively, in Sections 3.3 and 3.4. In Section 3.5, we compare the results and provide main findings. We conclude the Chapter with Section 3.6.

3.2 The Model's Description

We consider a quantity-setting Cournot duopoly model.[13] One of the firms is a consumer-friendly (CF) firm (hereafter referred to as firm 0) that cares for not only its profits but consumers surplus. The other is a for-profit (FP) firm (hereafter referred to as firm 1) that maximizes only its profits. Firms sell homogeneous output, $q_0 > 0$ and $q_1 > 0$, respectively, at the market clearing price $p(Q) = 1 - Q$ where $Q = q_0 + q_1$. We assume that both firms have identical technologies and the production cost function takes a quadratic form, $c(q_i) = \frac{1}{2} q_i^2$, $i \in \{0,1\}$.

Production leads to pollution, $e_i \geq 0$, but each firm can reduce pollution by undertaking abatement activities. Suppose that firm i chooses pollution abatement level $a_i > 0$. Then, the emission level can be reduced to $e_i = q_i - a_i$ by investing

[11] In the literature on environmental taxation, the rationale for a higher or lower optimal tax level depends on the relative effects of distortions, such as market powers between the related markets with abatement technologies, excessive or insufficient entry, and externality. See, for example, Canton et al. (2005), Requate (2007) and Lee and Park (2011) among others.

[12] In the literature on CSR, different approaches on the objectives of a consumer-friendly firm emitting emissions have been proposed. For example, Liu et al. (2015), Lambertini and Tampieri (2015) and Garcia et al. (2018) considered net consumer surplus or different weights on consumer surplus and environmental damages in the objectives of the firms with CSR-initiatives, while Lee and Park (2017) and Hirose et al. (2017) emphasized environmental damages only. In Appendix B.3, we examine the case in Liu et al. (2015) where the consumer-friendly firm cares for net consumer surplus and show that most findings in the analysis hold.

[13] Our model could be extended to the oligopoly model without further insights gained.

an amount of $\left(\frac{k}{2}\right) a_i^2$ in abatement, which is characterized by decreasing returns.[14] Note that a lower value of k implies higher efficiency of the abatement technology.

The extent of environmental damage due to pollution by the industry is given by $ED = \frac{(\sum_i e_i)^2}{2}$, where the marginal environmental damage is $MED = \sum_i e_i$. The government imposes an environmental tax on the emission level, for which the uniform tax rate is . The total tax revenue is $T = t\sum_i e_i$.

The profit of CF firm is given by $\pi_0 = p \cdot q_0 - \frac{1}{2}q_0^2 - t \cdot e_0 - \frac{k}{2}a_0^2$. We assume that the CF firm maximizes profits plus a fraction of consumer surplus (CS) . Thus, the payoff that CF firm maximizes is as follows:

$$V_0 = \pi_0 + \theta CS \tag{3.1}$$

where $CS = \frac{Q^2}{2}$. The parameter $\theta \in (0,1)$ measures the degree of concern on consumer surplus that the CF firm has, which is exogenously given.

The FP firm seeks only for profit maximization:

$$\pi_1 = p \cdot q_1 - \frac{1}{2}q_1^2 - t \cdot e_1 - \frac{k}{2}a_1^2 \tag{3.2}$$

The social welfare is the sum of consumer surplus, CS, the profits of both firms, $\pi_0 + \pi_1$, and tax revenue, T, minus environmental damage, ED:

$$W = CS + \pi_0 + \pi_1 + T - ED \tag{3.3}$$

To guarantee non-negative emissions in the analysis, we assume the followings:

A3.1. The efficiency parameter of abatement technology is such that

$$k \geq \underline{k}(\theta) = \frac{1}{4(2-\theta)}\left(\sqrt{400 - 544\theta + 248\theta^2 - 8\theta^3 + \theta^4} - (20 - 20\theta + \theta^2)\right).$$

Note that $\underline{k}(0) = 0$ and $\underline{k}(\theta)$ increases on θ.

We shall consider two alternative policy regimes, each featuring a three-stage game between a welfare-maximizing regulator and firms, to examine the properties of either a committed or a non-committed policy regime regarding environmental policy. In the former case of the *committed policy regime*, the regulator sets the emission tax then the firms, taking the tax rate as given, choose abatement

[14] The particular choice of the end-of-pipe technology in the specification of the pollution generation process is made for the sake of simplifying the analysis where there is no strategic effect under the committed regime.

investment simultaneously and independently. In the latter case of the *non-committed policy regime*, firms first select their abatement levels and then the regulator sets the emission tax. Finally, in both regimes, the firms select outputs in the third stage.

3.3 The Committed Policy Regime

In the third stage, firms 0 and 1 choose their outputs to maximize (3.1) and (3.2), respectively, given the emission tax rate, t . Using the first-order conditions we get the following equilibrium output level of each firm and total outputs:

$$q_0 = \frac{(1-t)(2+\theta)}{2(4-\theta)}, q_1 = \frac{(1-t)(2-\theta)}{2(4-\theta)}, Q = \frac{2(1-t)}{4-\theta} \qquad (3.4)$$

Note that each firm´s output decreases in the emission tax. Also if the concern on consumer surplus rises, the CF firm is more aggressive and thus increases its output while the FP firm decreases the output. However, the total outputs increases.

In the second stage, firms choose abatement efforts to maximize their payoffs. Firm 0 chooses a_0 that maximizes (3.1) while firm 1 chooses a_1 that maximizes (3.2). Solving these problems gives the equilibrium abatement level as a function of the tax:

$$a_i = \frac{t}{k}, \qquad i \in \{0,1\} \qquad (3.5)$$

that defines a positive relationship between abatement and the emission tax. Note that there is no strategic interaction between the firms.

In the first stage, the government sets the emission tax that maximizes social welfare in (3.3). Solving the first-order condition yields the optimal emission tax, which is given by[15]

$$t^c = \frac{k(8(4-\theta) + k(2+\theta)^2)}{D} \qquad (3.6)$$

where $D = k^2(20+\theta^2) + 4k(32-12\theta+\theta^2) + 8(4-\theta)^2 > 0$. We employ superscript *c* to denote the equilibrium under the committed policy regime. From (3.6) the equilibrium output, abatement and emission levels are obtained:

$$q_0^c = \frac{2(2+k)(4-\theta+k)(2+\theta)}{D} \qquad (3.7)$$

[15] Solving this problem gives the following first order condition: $-\frac{dED}{dt} = -(\mathbf{1} - \boldsymbol{Q}(\boldsymbol{t}))\frac{dQ}{dt} + \sum_{i=0}^{1} \boldsymbol{q}_i(\boldsymbol{t})\frac{dq_i}{dt} + \boldsymbol{k}\sum_{i=0}^{1} \boldsymbol{a}_i(\boldsymbol{t})\frac{da_i}{dt}$ where the left-hand side measures the marginal benefit of taxation that is given by the reduction in environmental damages associated to an increase in the emission tax rate and the right-hand side the marginal cost of taxation that has three components: the decrease in consumer surplus coming from the fall in output market, the decrease in the output of each firm, the raise in investment costs all caused by an increase in the emission tax rate.

$$q_1^c = \frac{2(2+k)(4-\theta+k)(2-\theta)}{D}$$

$$a_0^c = a_1^c = \frac{8(4-\theta)+k(2+\theta)^2}{D}$$

$$e_0^c = \frac{4k(5+k)+2(8+2k+k^2)\theta-(4+3k)\theta^2}{D}$$

$$e_1^c = \frac{4k(5+k)-2(8+10k+k^2)\theta+(4+k)\theta^2}{D}$$

In equilibrium under the committed policy regime, the CF firm's output is larger than that of the FP firm's, but both firms make the same abatement effort; therefore the CF firm's emission level is also larger than its rival's. Note that $\partial q_0^c/\partial\theta > 0$, $\partial q_1^c/\partial\theta < 0$ and $\partial a_i^c/\partial\theta > 0$, $i \in \{0,1\}$ for any $\theta\epsilon(0,1)$.

Finally, we have the resulting profits of the firms, environmental damage, and social welfare:

$$\pi_0^c = \frac{4(2+k)^2(4+k-\theta)^2(2+\theta)(6-5\theta)+k(8(4-\theta)+k(2+\theta)^2)^2}{2D^2}$$

$$\pi_1^c = \frac{12(2+k)^2(4+k-\theta)^2(2-\theta)^2+k(8(4-\theta)+k(2+\theta)^2)^2}{2D^2}$$

$$MED^c = \frac{2k(20+4k-8\theta-\theta^2)}{D} \tag{3.8}$$

$$ED^c = \frac{2k^2(20+4k-8\theta-\theta^2)^2}{D^2}$$

$$W^c = \frac{(2+k)(4k+(2-\theta)(10+\theta))}{D}$$

Proposition 3.1 *Let assumption A3.1 be accepted. Under the committed policy regime,* $\pi_1^c < \pi_0^c$ *for any* $\theta \in (0,1)$.

It states that in equilibrium under the committed policy regime, the profit of CF firm is always larger than that of FP firm because the CF firm is more aggressive in production, which induces less production of FP firm.[16]

Proposition 3.2 *Under assumption A3.1, the committed policy regime implies:*[17]

[16] For more discussion on this point, see Lambertini and Tampieri (2015) and Garcia et al. (2018).

[17] The proofs are provided in Appendix B.2 with the comparable figures, instead of formal mathematics, if it is not straightforward.

1. $t^c \lesseqgtr MED^c$ *if* $\theta \lesseqgtr 2(-1+\sqrt{2}) \approx 0.828$;

2. $\frac{\partial t^c}{\partial \theta} > 0$ *and* $\frac{\partial (MED^c - t^c)}{\partial \theta} < 0$ *for any* $\theta \epsilon (0,1)$;

3. $\frac{\partial ED^c}{\partial \theta} \geq 0$ *and* $\frac{\partial W^c}{\partial \theta} \geq 0$ *if and only if* $0 < \theta \leq \frac{1}{2}\left(9-\sqrt{65}\right) \approx 0.468$ *and* $k \leq k_c(\theta) = \frac{4-8\theta}{\theta}$, *where* $k_c\left(\frac{1}{2}\left(9-\sqrt{65}\right)\right) = \underline{k}\left(\frac{1}{2}\left(9-\sqrt{65}\right)\right)$.

Item 1 of Proposition 3.2 states that as like the results in the previous literature on the oligopoly model with emission tax, with a small degree of consumer-friendliness the emission tax under the committed regime is lower than the marginal environmental damage.[18] But the tax rate increases as θ increases and thus, interestingly, the opposite result occurs with a high value of θ. Therefore, as the concern on consumer surplus rises, a consumer-friendly firm produces more outputs aggressively, which increases total outputs and total emissions even under higher abatement levels. Thus, the optimal emission tax will be higher than marginal environmental damage. Finally, item 3 of Proposition 3.2 states that both welfare and environmental damage are simultaneously decreasing or increasing depending on the values of θ and k. This result represents a typical trade off between welfare and environmental damage in the literature.

3.4 The Non-Committed Policy Regime

The last stage in production is the same as in the previous committed policy regime. In the second stage, the regulator chooses the welfare maximizing emission tax taking as given the firms' abatement levels. The first order condition of this problem yields

$$t = \frac{(2+\theta)^2 - 4(4-\theta)(a_0 + a_1)}{20 + \theta^2} \tag{3.9}$$

This expression defines an inverse relationship between firms' abatement investments and the emission tax, that is, the regulator decreases the emission tax rate in response to an increase in the firms' abatement levels. Thus, firms can strategically use its choice of abatement to influence taxation: by increasing investment in emission-reducing activities, the firms can expect a lower emission tax. Also as the concern on consumer surplus increases so does the emission tax.
In the first stage, firms choose their abatement efforts taking into account how the regulator is going to respond. Firm 0 chooses a_0 that maximizes (3.1) while firm 1

[18] For example, Shaffer (1995) and Lee (1999) examined the blockaded-entry and free-entry models, respectively, and showed that the optimal emission tax might fall short of marginal environmental damage. Further analysis on the rationale for a higher or lower optimal tax level, see Canton et al. (2005), Lee and Park (2011) and Requate (2007) among others.

chooses a_1 that maximizes (3.2). Solving these problems gives the following reaction functions:

$$a_0 = \frac{128 + 128\theta + 4\theta^2 + 4\theta^3 + \theta^4 - 4(68 - 32\theta + 9\theta^2 - \theta^3)a_1}{592 - 208\theta + 52\theta^2 - 8\theta^3 + k(20 + \theta^2)^2}$$
$$a_1 = \frac{128 + 32\theta + 36\theta^2 + 4\theta^3 + \theta^4 - 4(68 - 8\theta + \theta^2 - \theta^3)a_0}{592 - 112\theta + 20\theta^2 - 8\theta^3 + k(20 + \theta^2)^2} \quad (3.10)$$

Since the slope of the reaction functions is negative, abatement efforts are strategic substitutes. This is in contrast to the commitment case where $\partial a_i / \partial a_j = 0$. Solving the reaction functions we derive the following equilibrium abatement efforts:

$$a_0^{nc} = \frac{4(512 + 864\theta - 272\theta^2 + 36\theta^3 - 8\theta^4 - \theta^5) + k(20 + \theta^2)(128 + 128\theta + 4\theta^2 + 4\theta^3 + \theta^4)}{N}$$
$$a_1^{nc} = \frac{4(512 - 480\theta + 272\theta^2 - 44\theta^3 + 8\theta^4 - \theta^5) + k(20 + \theta^2)(128 + 32\theta + 36\theta^2 + 4\theta^3 + \theta^4)}{N} \quad (3.11)$$

where $N = (4(4 - \theta) + k(20 + \theta^2)) \cdot H > H = 864 - 240\theta + 56\theta^2 - 12\theta^3 + k(20 + \theta^2)^2 > 0$. We also employ superscript *nc* to denote the equilibrium under the non-committed policy regime.

Proposition 3.3 *Let A3.1 be true. Under the non-committed policy regime, one has* $a_0^{nc} > a_1^{nc}$ *for any* $\theta \in (0,1)$.

It states that CF firm is more aggressive in investing abatement technology, which induces a larger amount of total abatement under the non-committed policy regime. Note that $\partial a_0^{nc} / \partial \theta > 0$ and $\partial (a_0^{nc} + a_1^{nc}) / \partial \theta > 0$ for any $\theta \epsilon (0,1)$.
The optimal emission tax is:

$$t^{nc} = \frac{k(2 + \theta)^2(20 + \theta^2) - 4(8 - 12\theta - 2\theta^2 + \theta^3)}{H} \quad (3.12)$$

From (3.4) and (3.12) the equilibrium output and emission levels are obtained:

$$q_0^{nc} = \frac{2(2+\theta)\big(k(20+\theta^2)+2(28-2\theta+\theta^2)\big)}{H}$$

$$q_1^{nc} = \frac{2(2-\theta)\big(k(20+\theta^2)+2(28-2\theta+\theta^2)\big)}{H}$$

$$e_0^{nc} = \frac{2k^2(20+\theta^2)^2(2+\theta)+k(20+\theta^2)(160-16\theta-12\theta^2-\theta^4)+4(384-704\theta+176\theta^2-20\theta^3+4\theta^4+\theta^5)}{N} \tag{3.13}$$

$$e_1^{nc} = \frac{2k^2(2-\theta)(20+\theta^2)^2+k(20+\theta^2)(160-208\theta-12\theta^2-8\theta^3-\theta^4)+4(384-256\theta-80\theta^2+12\theta^3-4\theta^4+\theta^5)}{N}$$

In equilibrium under the non-committed policy regime, the CF firm's output and abatement levels are larger than those of the FP firm. Thus, the emissions generated by the firms depend on θ and k.

Proposition 3.4 *Under assumption A3.1, the non-committed policy regime provides* $e_0^{nc} \le e_1^{nc}$ *if and only if* $0 < \theta \le \theta_e \approx 0.33$ *and* $k \le k_e(\theta)$*, where* $k_e(\theta)$ *satisfies that* $e_0^{nc}(k_e;\theta) = e_1^{nc}(k_e;\theta)$ *and* $k_e(\theta_e) = \underline{k}(\theta_e)$*.*

It states that the emissions generated by the CF firm can be less than those generated by the FP firm if its consumer-friendliness is low and the efficiency of abatement technology is relatively high. Note that $\partial q_0^{nc}/\partial\theta > 0$ and $\partial q_1^{nc}/\partial\theta < 0$ for any $\theta\epsilon(0,1)$.

Finally, we have the resulting profits of the firms, environmental damage, and social welfare:[19]

$$\pi_0^{nc} = \frac{\rho_4(\theta)k^4+\rho_3(\theta)k^3+\rho_2(\theta)k^2+\rho_1(\theta)k+\rho_0(\theta)}{2N^2},$$

$$\pi_1^{nc} = \frac{\lambda_4(\theta)k^4+\lambda_3(\theta)k^3+\lambda_2(\theta)k^2+\lambda_1(\theta)k+\lambda_0(\theta)}{2N^2},$$

$$MED^{nc} = \frac{2\big(96-96\theta-12\theta^2-4\theta^3-\theta^4+4k(20+\theta^2)\big)}{H}, \tag{3.14}$$

$$ED^{nc} = \frac{2\big(96-96\theta-12\theta^2-4\theta^3-\theta^4+4k(20+\theta^2)\big)^2}{H^2},$$

$$W^{nc} = \frac{\sigma_4(\theta)k^4+\sigma_3(\theta)k^3+\sigma_2(\theta)k^2+\sigma_1(\theta)k+\sigma_0(\theta)}{N^2}$$

Proposition 3.5 *Let assumption A3.1 be fulfilled. Under the non-committed policy regime,* $\pi_1^{nc} \le \pi_0^{nc}$ *if and only if* $0 < \theta \le \theta_{\pi 1s}(k)$ *where* $\pi_1^{nc}(k;\theta_{\pi 1s}) = \pi_0^{nc}(k;\theta_{\pi 1s})$ *and* $\theta_{\pi 1s}(k) \ge 0.9428$*.*

[19] For the sake of expositional convenience, we provide $\boldsymbol{\rho_i(\theta)}$, $\boldsymbol{\lambda_i(\theta)}$ and $\boldsymbol{\sigma_i(\theta)}$ in Appendix B.1.

It states that in equilibrium under the non-committed policy regime, the profit of CF firm can be larger than that of FP firm if the consumer-friendliness is not so high. It implies that concerning a certain portion of consumer surplus is beneficial to a CF firm irrespective of the timing of the commitment to the environmental policy.

Proposition 3.6 *Under assumption A3.1, the non-committed policy regime yields:*

1. $t^{nc} \lesseqgtr MED^{nc}$ *if* $\theta \lesseqgtr 2(-1+\sqrt{2}) \approx .828$*;*

2. $\frac{\partial t^{nc}}{\partial \theta} > 0$ *and* $\frac{\partial (MED^{nc} - t^{nc})}{\partial \theta} < 0$ *for any* $\theta \in (0,1)$*;*

3. $\frac{\partial MED^{nc}}{\partial \theta} < 0$ *and* $\frac{\partial ED^{nc}}{\partial \theta} < 0$ *for any* $\theta \in (0,1)$*;*

4. $\frac{\partial W^{nc}}{\partial \theta} \geq 0$ for any $0 < \theta \leq \theta_{W_{nc}} \approx 0.489$ if and only if $k \leq k_{W_{nc}}(\theta)$, where $k_{W_{nc}}(\theta)$

satisfies that $\frac{\partial W^{nc}}{\partial \theta} = 0$ and $k_{W_{nc}}(\theta_{W_{nc}}) = \underline{k}(\theta_{W_{nc}})$.

The results in item 1 of Propositions 3.6 state that with a small degree of consumer-friendliness the emission tax under the non-committed policy regime is also lower than the marginal environmental damage. But the tax rate increases as θ increases and thus the opposite occurs with a very high value of θ. This result is the same with that under the committed policy regime. However, the inequaltites obtained in items 3 and 4 of Proposition 3.6 state that it is possible that welfare is increasing and environmental damage is decreasing with small values of θ and k. This result sharply contrast to the result under the committed policy regime where a trade off between welfare and environmental damage exists.

3.5 Comparing Policy Regimes

In this section, we provide comparisons between the committed and non-committed policy regimes and summarize our findings in a number of propositions.

Proposition 3.7 *Let A3.1 be true. Then* $t^{nc} < t^{c}$ *for any* $\theta \in (0,1)$.

The committed emission tax is larger than the non-committed one. The intuition is as follows: Under the non-committed policy regime, due to the time-inconsistency problem, each firm has a strategic incentive to increase abatement in order to induce the regulator to impose a lower emission tax subsequently. It represents that the strategic incentive of innovation will ratchet down the regulator's ex-post possibility to decide tax rate, which is dependent on the strategic relationship between the firms. This aspect is absent when the regulator pre-commit to an emission tax.[20]

Proposition 3.8 *Let assumption A3.1 be accepted. Then*

1. $q_0^{nc} > q_0^c$, $q_1^{nc} > q_1^c$ *and* $Q^{nc} > Q^c$ *for any* $\theta \in (0,1)$
2. $a_0^{nc} \ge a_0^c$ *for any* $\theta \in (0,1)$ *if and only if* $k \ge k_{a_0}$ *where* $k_{a_0}(\theta)$ *satisfies that* $a_0^{nc}(k_{a_0};\theta) = a_0^c(k_{a_0};\theta)$
3. $a_1^{nc} \ge a_1^{nc}$ *for any* $\theta \in (0,1)$ *if and only if* $k \ge k_{a_1}$ *where* $k_{a_1}(\theta)$ *satisfies that* $a_1^c(k_{a_1};\theta) = a_1^{nc}(k_{a_1};\theta)$
4. $a_0^{nc} + a_1^{nc} \ge a_0^c + a_1^c$ *for any* $\theta \in (0,1)$ *if and only if* $k \ge k_{aa}$ *where* $k_{aa}(\theta)$ *satisfies that* $a_0^c(k_{aa};\theta) + a_1^c(k_{aa};\theta) = a_0^{nc}(k_{aa};\theta) + a_1^{nc}(k_{aa};\theta)$

It states that compared to the committed policy regime, both firms increase not only outputs but abatement investments under the non-commitment policy regime when the efficiency of abatement technology is relatively low.

Proposition 3.9 *Let A3.1 be satisfied and* $\theta \in (0,1)$. *Then*

1. $\pi_0^c \le \pi_0^{nc}$ if and only if $k \ge k_{\pi_0}$, where $k_{\pi_0}(\theta)$ satisfies that $\pi_0^c(k_{\pi_0};\theta) = \pi_0^{nc}(k_{\pi_0};\theta)$
2. $\pi_1^c \le \pi_1^{nc}$ if and only if $k \ge k_{\pi_1}$, where $k_{\pi_1}(\theta)$ satisfies that $\pi_1^c(k_{\pi_1};\theta) = \pi_1^{nc}(k_{\pi_1};\theta)$.

It implies that both firms can earn higher profits under the non-committed policy regime when the efficiency of abatement technology is relatively low.

Proposition 3.10 *Let assumption A3.1 be true. Then*

1. $ED^c \ge ED^{nc}$ if and only if $\theta_{ED}(k) \le \theta < 1$, where $\theta_{ED}(k)$ satisfies that $e_0^c(k;\theta_{ED}(k)) + e_1^c(k;\theta_{ED}(k)) = e_0^{nc}(k;\theta_{ED}(k)) + e_1^{nc}(k;\theta_{ED}(k))$ and $\theta_{ED}(k) \ge 0.44818$;
2. $W^c \le W^{nc}$ *if one of the following conditions is satisfied*
   (a) $0 < \theta \le \theta_{W_1} \approx 0.568$ *and* $k > k_{W_1}$ *or,*
   (b) $\theta_{W_1} \le \theta \le \theta_{W_2} \approx 0.585$ *and* $k_{W_2} \le k \le k_{W_3}$,

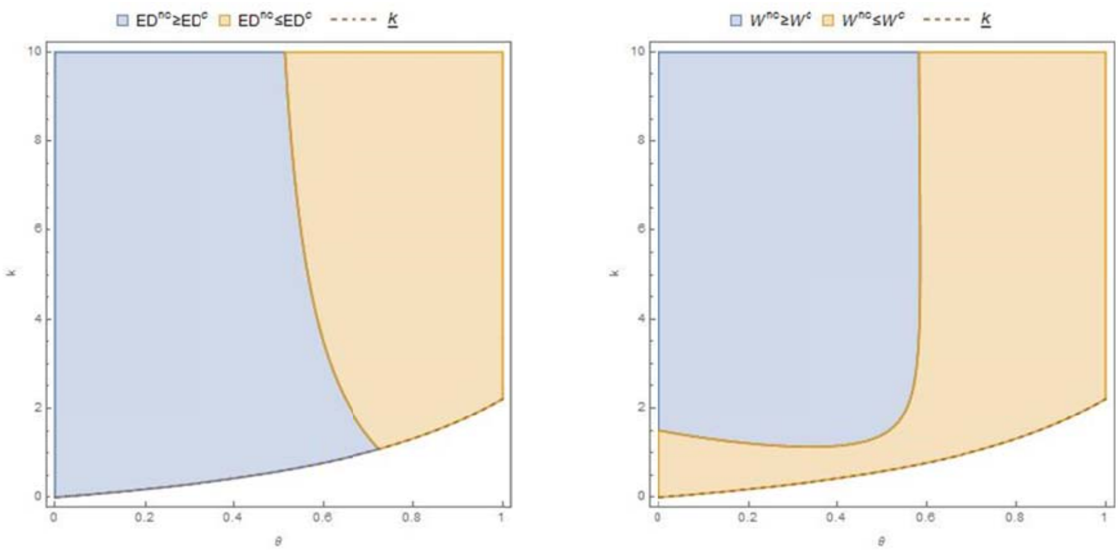
where for each $i =,1,2,3$, *the value of* $k_{W_i}(\theta)$, *solves the equations* $W^c(k_{W_i};\theta) = W^{nc}(k_{W_i};\theta)$, $k_{W_1}(\theta_{W_1}) = k_{W_2}(\theta_{W_1})$, *and* $k_{W_2}(\theta_{W_2}) = k_{W_3}(\theta_{W_2})$.

Otherwise, $W^c > W^{nc}$.

Therefore, with large θ and high k , the total emissions and thus environmental damage under the non-committed policy regime are smaller than the commitment one. Furthermore, with small θ and high k, the welfare under the non-committed

[20] This finding is also pointed out by Poyago-Theotoky and Teerasuwannajak (2002) and Moner-Colonques and Rubio (2015) in the context of non-committed environmental policy regime, but they did not consider the role of consumer-friendly firm.

policy regime is larger than the commitment one. We can plot Fig. 3.1.a and 3.1.b, and show the comparisons of environmental damage and welfare between the two different policy regimes, respectively. We can also plot Fig. 3.2 and show that (i) the non-committed policy regime is better than the committed one, i.e., $ED^c \geq ED^{nc}$ and $W^c \leq W^{nc}$ if θ is intermediate and k is large while (ii) the committed policy regime is better than the non-committed one, i.e., $ED^c \leq ED^{nc}$ and $W^c \geq W^{nc}$ if both θ and k are small.



(a) ED comparison (b) Welfare Comparison

Fig. 3.1 ED and Welfare Comparisons

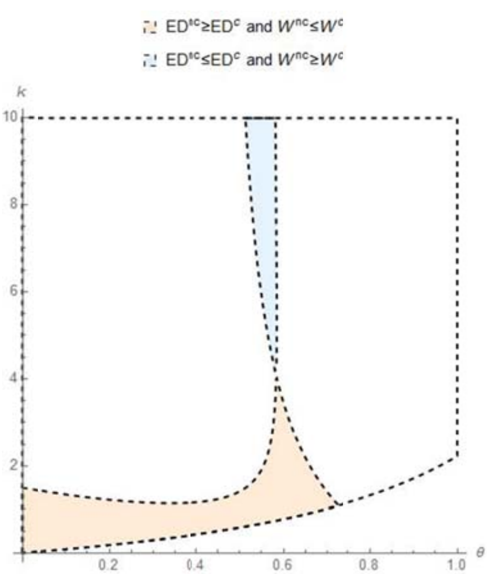


Fig. 3. 2 Commitment vs Non-commitment

3.6 Main Findings and Future Work

We have considered CSR initiatives of the firms and examined the timing of government's commitment to the environmental tax policy. We have emphasized the heterogeneity of objectives and its impact on the time inconsistency problem in which firms' strategic decisions on production and abatement activities might result in different welfare consequences. We have shown that the optimal emission tax under the committed policy regime is always higher than that under the non-committed one, but both taxes can be higher than marginal environmental damage when the consumer-friendliness is high enough. We also have shown that under the non-committed policy the firms decide not only more outputs and higher profits but also more abatement and lower emission when the consumer-friendliness is high and the efficiency of abatement technology is not so high. Therefore, the emergence of a consumer-friendly firm might yield better outcomes to the welfare and environmental quality without the commitment to the environmental policy under certain conditions. These results show that CSR initiatives can play a significant role in the design and implementation of environmental policy. The importance of CSR needs to be further examined in some alternative settings under different market structures to check the robustness of the results obtained in this paper. This has to be left for future research.

Chapter 4 Conclusion and Future Work

In this thesis, two oligopoly models were used to investigate the consequences of the implementation of two different public policies. The latter was done by resorting to the formulation of multi-level games. The players make their decisions to maximize their payoff functions. The equilibrium was found for each game, considering the public policy to be investigated and the homogeneity or heterogeneity of the objectives of the companies. Finally, the consequences for companies in the case of the first game and for society and the environment in the case of the second study were reviewed.

These studies provide useful insights about the implications of the application of the public policies. Particularly, the first study was important to establish that the technical advantage plays a crucial role in determining if globalization is good or not for a company. The second study tells us that the emergence of a consumer-friendly firm in a regime unable to commit credibly to a tax policy could be good for welfare and environmental quality. These valuable results should be taken into account by governments when designing public policies. Also, they are expected to be useful for companies when making their decisions.

It would be interesting to analyze the effects of globalization considering the heterogeneity of objectives, this is, in the presence of a consumer-friendly company. The climate change is a global problem, and analysis that includes the different environmental policy instruments applied by the countries in a single global market would be interesting as well. Other kinds of policy instruments considered or implemented around the world are Emissions Trading System and hybrid instruments. Those topics are left for future research.

Appendix A. "Effects of Globalization Under Consistent Conjectures"

A.1

Profits before globalization

$$\pi_i = \begin{cases} \dfrac{(c-b)^2}{2(2d+a_i)}, & if\ \dfrac{c-b}{2d+a_i} > \dfrac{\bar{Q}}{2}; \\ \dfrac{1}{8}\bar{Q}\big(4(c-b) - \bar{Q}(2d+a_i)\big), & if\ \dfrac{c-b}{2d+a_i} \le \dfrac{\bar{Q}}{2}. \end{cases} \qquad (1')$$

Equilibrium price, outputs, and profits. We know from (2.9) that $\sum_{j=0}^{1}\frac{1}{v_j+a_j} = \frac{1}{v_i+a_i} + \frac{1}{v_i} - \frac{2}{d}$, $i \in \{0,1\}$. After some algebraic manipulations one yields:

$$Q = \frac{\sum_{j=0}^{1}\dfrac{c-b}{v_j+a_j}}{\dfrac{d}{2}\left(\dfrac{1}{v_i+a_i} + \dfrac{1}{v_i}\right)}, \qquad p_w = c - \frac{\sum_{j=0}^{1}\dfrac{c-b}{v_j+a_j}}{\dfrac{1}{v_i+a_i} + \dfrac{1}{v_i}}, \qquad (2')$$

$$\xi_i(\tilde{q}_i) = \frac{(2v_i(c-b))^2}{2d^2(2v_i+a_i)}. \qquad (3')$$

Profit Ratios in Situation 1

From (2.8), $p_w = (v_i + a_i)\tilde{q}_i + b$, and from A1.1, $p_i(\bar{q}_i) = c - d\bar{q}_i$.

Plug in these values in (2.12) and note that

$$(c - d\bar{q}_i)\bar{q}_i - \frac{1}{2}a_i\bar{q}_i^2 - b\bar{q}_i = \frac{1}{2}\frac{(c-b)^2}{(2d+a_i)} = \frac{1}{2}(2d+a_i)\bar{q}_i^2,$$

then (2.12) can be rewritten as $R_i = \frac{2v_i+a_i}{2d+a_i}\left(\frac{\tilde{q}_i}{\bar{q}_i}\right)^2$.

In the equilibrium, when $p_w < \bar{P}$, the total supply output equals the demand in the market. Then, from A2.1, $p_w = c - \frac{d}{2}Q$, where $Q = \tilde{q}_0 + \tilde{q}_1$.

Insert the equilibrium outputs in (2.11) to obtain the total output and the equilibrium price p_w: $Q = p_w\sum_{j=0}^{1}\frac{1}{v_j+a_j} - \sum_{j=0}^{1}\frac{b}{v_j+a_j}$.

Then $\boldsymbol{Q} = \frac{\sum_{j=0}^{1} \frac{c-b}{v_j+a_j}}{1+\frac{d}{2}\sum_{j=0}^{1}\frac{1}{v_j+a_j}}$. We know from (2.9) that $\sum_{j=0}^{1} \frac{1}{v_j+a_j} = \frac{1}{v_i+a_i} + \frac{1}{v_i} - \frac{2}{d},\ \boldsymbol{i} \in \{\mathbf{0}, \mathbf{1}\}$, hence $\boldsymbol{Q} = \frac{\sum_{j=0}^{1} \frac{c-b}{v_j+a_j}}{\frac{d}{2}\frac{1}{v_i+a_i}+\frac{1}{v_i}}$. The equilibrium price $\boldsymbol{p_w} = \boldsymbol{c} - \boldsymbol{dQ}/\mathbf{2}$ can be plugged in (2.11), hence the output values ratio of firm $\boldsymbol{i}$ is:

$$\frac{\tilde{q}_i}{\bar{q}_i} = \frac{2d+a_i}{v_i+a_i} - \frac{(2d+a_i)(\sum_{j=0}^{1} \frac{c-b}{v_j+a_j})}{(c-b)(2+\frac{a_i}{v_i})}.$$

Substitute this ratio in $\boldsymbol{R_i} = \frac{2v_i+a_i}{2d+a_i}\left(\frac{\tilde{q}_i}{\bar{q}_i}\right)^2$ and after a little of algebra obtain $\boldsymbol{R_i} = \frac{2d+a_i}{2v_i+a_i}\left(\mathbf{1} - \frac{v_i}{v_{-i}+a_{-i}}\right)^2$.

Note from (2.9) that $\frac{v_i}{v_{-i}+a_{-i}} = \mathbf{1} - \frac{2}{d}\boldsymbol{v_i}$. Then $\boldsymbol{R_i} = \frac{2d+a_i}{2v_i+a_i}(\frac{2}{d}\boldsymbol{v_i})^2$.

The desired result is obtained by plugging in the influence coefficients (2.10) in the last formula for $\boldsymbol{R_i}$.

Functions Omitted in the Text for Space Issues:

$$\lambda_1(a_i, a_{-i}, d) = \left(\frac{2\sqrt{\frac{a_i^2}{4} + \frac{\Gamma}{K_{-i}}}}{2d + a_i}\right)^{\frac{1}{2}}$$

$$\lambda_2(a_i, a_{-i}, d) = 1 - \frac{2}{d}\left(-\frac{a_i}{2} + \sqrt{\frac{a_i^2}{4} + \frac{\Gamma}{K_{-i}}}\right)$$

$$\chi_i(a_i, a_{-i}, d) = -(8a_2d^3 + 6a_id^2(3a_2 + d) + a_i^2d(14a_2 + 9d) + 4a_i^3(a_2 + d)) + (2d^2(3a_2 + d) + a_id(10a_2 + 7d) + 4a_i^2(a_2 + d))\sqrt{\frac{d + a_i}{d + a_2}(da_i + da_2 + a_1a_{-i})}$$

$$\tilde{\chi}_i(\rho, \sigma) = -(8\rho^3 + 4(\rho + 3)\rho^2\sigma + 2(\rho + 2)\rho\sigma^2) - (2(\rho + 3)\rho^2 + 4(\rho + 1)\sigma^2 + (7\rho + 10)\rho\sigma)\left(\sigma - \sqrt{(\rho + \sigma)\left(\frac{\rho}{1 + \rho} + \sigma\right)}\right)$$

A.2 Proofs in Situation 1

Proposition 2.1. We say that profit degrades when the benefits earned after globalization are less than before, i.e. $\boldsymbol{R_i} < \mathbf{1}$. As all parameters are positive, formula $\boldsymbol{R_i < 1}$ is equivalent to $\left(\frac{2}{d}\left(-\frac{a_i}{2}+\sqrt{\frac{a_i^2}{4}+\frac{\Gamma}{K_{-i}}}\right)\right)^2 < \frac{2\left(\sqrt{\frac{a_i^2}{4}+\frac{\Gamma}{K_{-i}}}\right)}{2d+a_i}$ which leads to (2.15).

From (2.9), $\frac{v_i}{v_{-i}+a_{-i}} = \mathbf{1}-\frac{2}{d}v_i$. Recall that $v_i > 0, i = 0, 1$, if $\tau = -\frac{2}{d}$, and the demand and cost functions' parameters are also positive, then $0 < v_i < \frac{d}{2}$. Hence, given (2.10), we have $0 < 2\sqrt{\frac{a_i^2}{4}+\frac{\Gamma}{K_{-i}}} < d + a_i$, therefore $0 < \left(\frac{2\left(\sqrt{\frac{a_i^2}{4}+\frac{\Gamma}{K_{-i}}}\right)}{2d+a_i}\right)^{1/2} < 1$.

Assumptions A1.2 and A2.2 ensure that both firms actually produce maintain nonzero output levels before and after globalization, then $\frac{\tilde{q}_i}{\bar{q}_i} > 0$. Since d, a_i, v_i are positive, the product $\frac{2v_i+a_i}{2d+a_i}\left(\frac{\tilde{q}_i}{\bar{q}_i}\right)$ is positive, too. Similar to the proofs in *Appendix A.1*, substitute the value of $\frac{\tilde{q}_i}{\bar{q}_i}$ in the formulas for the ratios and find $\frac{2v_i+a_i}{2d+a_i}\left(\frac{\tilde{q}_i}{\bar{q}_i}\right) = \frac{2}{d}v_i > 0$. Therefore, the second element of the sum in (15) is also smaller than 1.

Proposition 2.2. Differentiate (2.14) by a_{-i}, and a simplification yields $\frac{\partial R_i}{\partial a_{-i}} = \frac{2d+a_i}{4\left(\sqrt{\frac{a_i^2}{4}+\frac{\Gamma}{K_{-i}}}\right)^3}\left(\frac{2}{d}\right)^2\left(\frac{\Gamma}{K_{-i}}\right)\cdot\frac{K_i}{K_{-i}^2} > 0$

Proposition 2.3.

a) We want to show that, if $a_i < a_{-i}$ then

$$R_{-i} = \frac{2d + a_{-i}}{2v_{-i} + a_{-i}}\left(\frac{2}{d}v_{-i}\right)^2 < 1. \tag{4'}$$

Expression (4') is equivalent to

$$(2d + a_{-i})(v_{-i})^2 < (2v_{-i} + a_{-i})\left(\frac{d}{2}\right)^2. \tag{5'}$$

By substituting v_{-i}, rewrite formula (5') as follows:

$$\frac{(2d + a_{-i})(a_i(2a_{-i}(d + a_{-i}) + d^2) + a_{-i}d(2a_{-i} + d))}{4(d + a_i)} - (2da_{-i} + a_{-i}^2)\sqrt{\frac{a_{-i}^2}{4} + \frac{d\left(a_{-i} + a_i + \frac{2}{d}a_i a_{-i}\right)}{2\left(2 + \frac{2}{d}a_i\right)}} < \frac{1}{2}d^2\sqrt{\frac{a_{-i}^2}{4} + \frac{d\left(a_{-i} + a_i + \frac{2}{d}a_i a_{-i}\right)}{2\left(2 + \frac{2}{d}a_i\right)}}, \tag{6'}$$

which is tantamount to

$$\frac{(2d+a_{-i})(a_i(2a_{-i}(d+a_{-i})+d^2)+a_{-i}d(2a_{-i}+d))}{4(d+a_i)} < \left((2da_{-i}+a_{-i}^2)+\frac{1}{2}d^2\right)\sqrt{\frac{a_{-i}^2}{4}+\frac{d\left(a_{-i}+a_i+\frac{2}{d}a_ia_{-i}\right)}{2\left(2+\frac{2}{d}a_i\right)}}. \tag{7'}$$

Note that both sides of the inequality are positive, so we can square inequality (7') and after some algebraic manipulations obtain the following equivalent relationship:

$$(a_{-i}+d)(2a_{-i}(a_{-i}+2d)+d^2)^2(a_i+d)(a_id+a_{-i}(a_i+d)) > (a_{-i}+2d)^2(a_i(2a_{-i}(a_{-i}+d)+d^2)+a_{-i}d(2a_{-i}+d))^2, \tag{8'}$$

or, which is the same,

$$(a_{-i}+a_i)d^7+(5a_{-i}^2+3(a_{-i}-a_i)a_i)d^6+2a_{-i}(2a_{-i}^2+(a_{-i}-a_i)(3a_i+2(a_{-i}+a_i)))d^5 + a_{-i}^2(a_{-i}^2+(a_{-i}-a_i)(10a_i+2(a_{-i}+a_i)))d^4+4a_{-i}^3(a_{-i}-a_i)a_id^3 > 0. \tag{9'}$$

Inequality (9') is true since $\boldsymbol{a_i < a_{-i}}$.

b) Let $\boldsymbol{a_{-i} = a}$. Then, after some manipulations:

$$R_i = \frac{(2d+a_i)\left(a_i-\sqrt{\frac{d+a_i}{d+a}}\sqrt{da+da_i+aa_i}\right)^2}{d^2\sqrt{\frac{d+a_i}{d+a}}\sqrt{da+da_i+aa_i}},$$

$$R_{-i} = \frac{(2d+a)\left(a-\sqrt{\frac{d+a}{d+a_i}}\sqrt{da+da_i+aa_i}\right)^2}{d^2\sqrt{\frac{d+a}{d+a_i}}\sqrt{da+da_i+aa_i}}.$$

In this situation, $\boldsymbol{R_{-i} < R_i}$ if

$$\frac{d+a}{2d+a}\left(\sqrt{\frac{d+a_i}{d+a}}\sqrt{ad+a_id+aa_i}-a_i\right)^2 > \frac{d+a_i}{2d+a_i}\left(\sqrt{\frac{d+a}{d+a_i}}\sqrt{ad+a_id+aa_i}-a\right)^2. \tag{10'}$$

The last inequality is obtained by simplifying the terms in the original $\boldsymbol{R_{-i} < R_i}$. Note that if $\boldsymbol{a_i < a}$, then

$$\frac{d+a_i}{2d+a_i} < \frac{d+a}{2d+a}. \tag{11'}$$

Also, if $\boldsymbol{a_i < a}$, then $\frac{\boldsymbol{a_i}}{\boldsymbol{a_i+d}} < \frac{\boldsymbol{a}}{\boldsymbol{a+d}}$, because $\boldsymbol{g(x) = \frac{x}{x+d}}$ is an increasing function by $\boldsymbol{x}$, with $\boldsymbol{d > 0}$. Multiply both sides by $\boldsymbol{a - a_i > 0}$ to get $\frac{\boldsymbol{a_i}}{\boldsymbol{a_i+d}}(\boldsymbol{a - a_i}) < \frac{\boldsymbol{a}}{\boldsymbol{a+d}}(\boldsymbol{a - a_i})$, which is equivalent to $\boldsymbol{a_i\left(\frac{a+d}{a_i+d} - 1\right) < a\left(1 - \frac{a_i+d}{a+d}\right)}$. This inequality is tantamount, after some algebra, to:

$$\boldsymbol{(a - a_i)^2 > \left(\left(\sqrt{\frac{d+a}{d+a_i}} - \sqrt{\frac{d+a_i}{d+a}}\right)\sqrt{da + da_i + aa_i}\right)^2}.$$

Because of $\boldsymbol{a - a_i > 0}$, which implies that $\boldsymbol{\sqrt{\frac{d+a}{d+a_i}} - \sqrt{\frac{d+a_i}{d+a}} > 0}$, we have $\boldsymbol{a - a_i > \left(\sqrt{\frac{d+a}{d+a_i}} - \sqrt{\frac{d+a_i}{d+a}}\right)\sqrt{da + da_i + aa_i}}$.

Hence, $\boldsymbol{\left(\sqrt{\frac{d+a_i}{d+a}}\right)\sqrt{da + da_i + aa_i} - a_i > \left(\sqrt{\frac{d+a}{d+a_i}}\right)\sqrt{da + da_i + aa_i} - a}$. Note that both sides are positive, therefore:

$$\left(\sqrt{\frac{d + a_i}{d + a}}\sqrt{ad + a_i d + aa_i} - a_i\right)^2 > \left(\sqrt{\frac{d + a}{d + a_i}}\sqrt{ad + a_i d + aa_i} - a\right)^2. \qquad (12')$$

Inequalities (11’) and (12’) combined together imply the desired relationship (10’).

Proposition 2.4.

As $4a^6 + 16a^5 d + 20a^4 d^2 + 8a^3 d^3 < 4a^6 + 16a^5 d + 20a^4 d^2 + 8a^3 d^3 + a^2 d^4$ then $\left((2a^2 + 2ad)\sqrt{a(a + 2d)}\right)^2 < (ad^2 + 2a^3 + 4a^2 d)^2$.

Therefore, $(2a^2 + 2ad)\sqrt{a(a + 2d)} < (ad^2 + 2a^3 + 4a^2 d)$, given that both sides of the inequality are positive. Hence, $\sqrt{a(a + 2d)}\left(a - \sqrt{a(a + 2d)}\right)^2 < ad^2$, which entails that $\frac{\sqrt{a(a+2d)}\cdot\left(a-\sqrt{a(a+2d)}\right)^2}{ad^2} < 1$, and thus,

$$R = \frac{2d + a}{2\left(\sqrt{\frac{a^2}{4} + \frac{ad}{2}}\right)}\left(\frac{2}{d}\left(\frac{-a}{2} + \sqrt{\frac{a^2}{4} + \frac{ad}{2}}\right)\right) = \frac{\sqrt{a(a + 2d)}\left(a - \sqrt{a(a + 2d)}\right)^2}{ad^2}. \qquad (13')$$

On account of that, $\mathbf{R < 1}$.

A.3 Proofs in Situations 2 and 3

Proposition 2.5. Differentiate $\boldsymbol{R_1}$ by $\boldsymbol{a_0}$ to get

$$\frac{\partial R_1}{\partial a_0} = \frac{2d^2(d+a_1)(c-b)^2\Gamma}{\overline{Q}((d+a_0)(d+a_1)(a_0d+a_1d+a_0a_1))^{\frac{3}{2}}(4(c-b)-\overline{Q}(2d+a_1))}. \quad (14')$$

By assumption A1.2, $\boldsymbol{c - b > 0, i = 0, 1}$; $\boldsymbol{\Gamma}$ is positive by definition. The expression $4(c-b)-\overline{Q}(2d+a_1)$ is positive. Assumption A1.3 states $\overline{P} > max_{i\in\{0,1\}}\{a_i\overline{Q}/2 + b\}$, which is equivalent to $\frac{c-b}{2d+2a_i} > \frac{\overline{Q}}{4}$. Therefore, clearly,

$\frac{\partial R_1}{\partial a_0} > 0$.

The proof is complete.

A.4 Proof in Situation 4

Proposition 2.6. Observe that $\boldsymbol{R_i}$ in (2.19) for $\boldsymbol{i = 1}$ is the same $\boldsymbol{R_1}$ of (2.18). *See Proof of Proposition 2.5*

Appendix B. “The timing of Environmental Tax Policy with a Consumer-Friendly Firm”

B.1 The values of $\rho_i(\theta)$, $\lambda_i(\theta)$ and $\sigma_i(\theta)$

$\rho_0(\theta) \equiv 36438016 - 374865592\theta + 73564416\theta^2 + 26705592\theta^3 - 25436616\theta^4 + 9400032\theta^5 - 1884416\theta^6 + 25600\theta^7 - 1536\theta^8 - 128\theta^9$

$\rho_1(\theta) \equiv 16(7479296 - 59228816\theta - 239616\theta^2 + 8212448\theta^3 - 5103336\theta^4 + 1573312\theta^5 - 35440\theta^6 + 5856\theta^7 - 512\theta^8 + 48\theta^9 + 5\theta^{10})$

$\rho_2(\theta) \equiv 16(20 + \theta^2)(416512 - 2352264\theta - 67008\theta^2 + 368320\theta^3 - 18800\theta^4 + 3568\theta^5 - 788\theta^6 + 38\theta^7 - 8\theta^8 - \theta^9)$

$\rho_3(\theta) \equiv (20 + \theta^2)^2(142336 - 532480\theta - 31872\theta^2 + 8448\theta^3 - 3056\theta^4 + 608\theta^5 - 16\theta^6 + 8\theta^7 + \theta^8)$

$\rho_4(\theta) \equiv 4(20 + \theta^2)^4(2 + \theta)(6 - 5\theta)$

$\lambda_0(\theta) \equiv 128(4 - \theta)(71168 - 948480\theta + 49920\theta^2 - 15520\theta^3 + 4560\theta^4 - 928\theta^5 + 120\theta^6 - 16\theta^7 + \theta^8)$

$\lambda_1(\theta) \equiv 16(7479296 - 100147200\theta + 57405440\theta^2 - 19394560\theta^3 + 6186240\theta^4 - 1442560\theta^5 + 254880\theta^6 - 4576\theta^7 + 480\theta^8 - 48\theta^9 + 5\theta^{10})$

$\lambda_2(\theta) \equiv 16(20 + \theta^2)(416512 - 4651520\theta + 2486400\theta^2 - 626240\theta^3 + 204960\theta^4 - 3312\theta^5 + 476\theta^6 - 82\theta^7 - \theta^9)$

$\lambda_3(\theta) \equiv (20 + \theta^2)^2(142336 - 1361920\theta + 674560\theta^2 - 9728\theta^3 + 4880\theta^4 - 32\theta^5 + 112\theta^6 + 8\theta^7 + \theta^8)\lambda_4(\theta) \equiv 12(2 - \theta)^2(20 + \theta^2)^4$

$\sigma_0(\theta) \equiv 32(4 - \theta)^2(109056 - 38400\theta + 4352\theta^2 - 5760\theta^3 - 656\theta^4 - 352\theta^5 - 48\theta^6 - 8\theta^7 - \theta^8)$

$\sigma_1(\theta) \equiv 16(11329536 - 70881280\theta + 17346560\theta^2 - 668672\theta^3 + 44288\theta^4 - 19392\theta^5 + 2352\theta^6 + 48\theta^7 + 184\theta^8 + 36\theta^9 + 3\theta^{10} + \theta^{11})$

$\sigma_2(\theta) \equiv 2(20 + \theta^2)(4990976 - 20541440\theta + 438272\theta^2 - 207872\theta^3 - 13376\theta^4 - 13760\theta^5 - 1328\theta^6 - 480\theta^7 - 52\theta^8 - 4\theta^9 - \theta^{10})$

$\sigma_3(\theta) \equiv (20 + \theta^2)^2(214016 - 46080\theta + 15616\theta^2 - 5248\theta^3 - 336\theta^4 - 384\theta^5 - 40\theta^6 - 8\theta^7 - \theta^8)\sigma_4(\theta) \equiv 4(20 + \theta^2)^5$

B.2 Proofs

Proposition 3.3

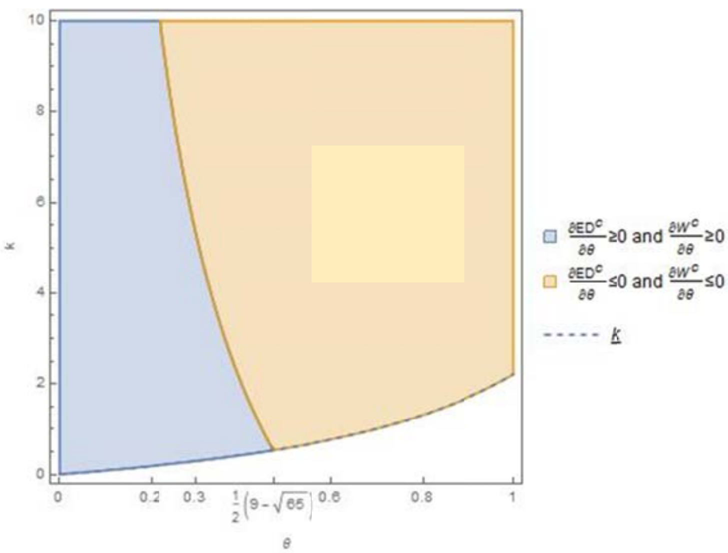


Fig. B.2. 1 Behavior of the derivatives $\frac{\partial ED^c}{\partial\theta}$ and $\frac{\partial W^c}{\partial\theta}$

Proposition 3.4

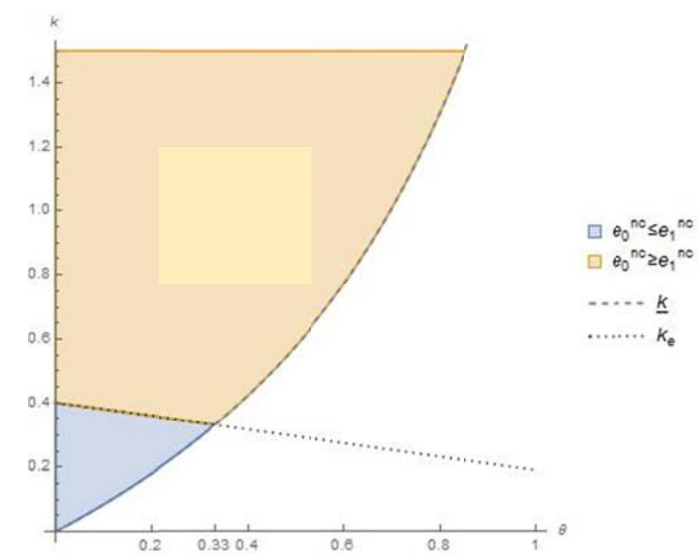


Fig. B.2. 2 e_0^{nc} **vs.** e_1^{nc}

Proposition 3.5

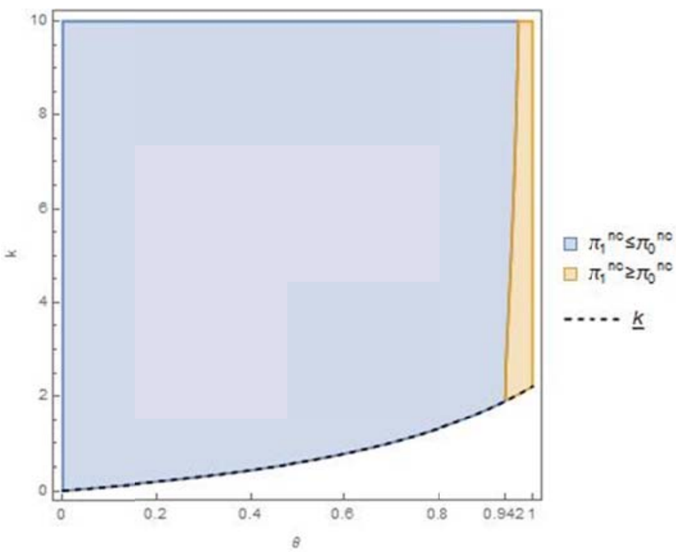


Fig. B.2. 3 π_1^{nc} **vs.** π_0^{nc}

Proposition 3.6 item 4

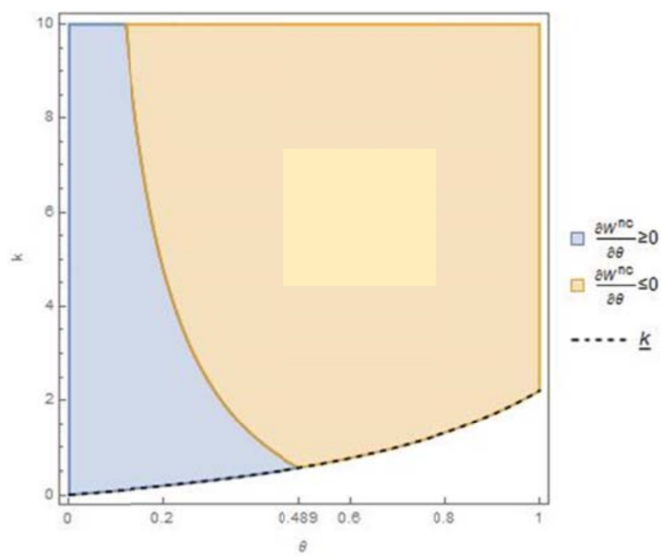
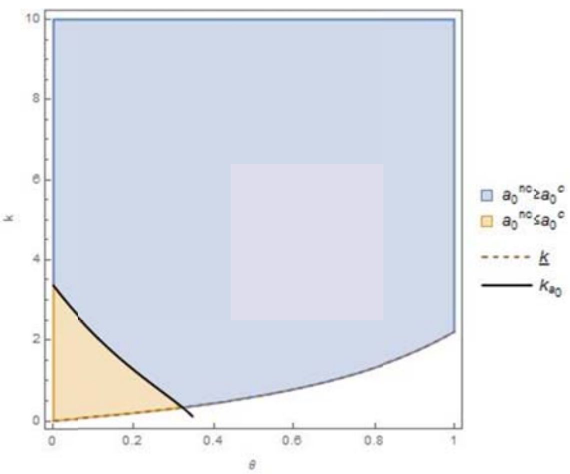
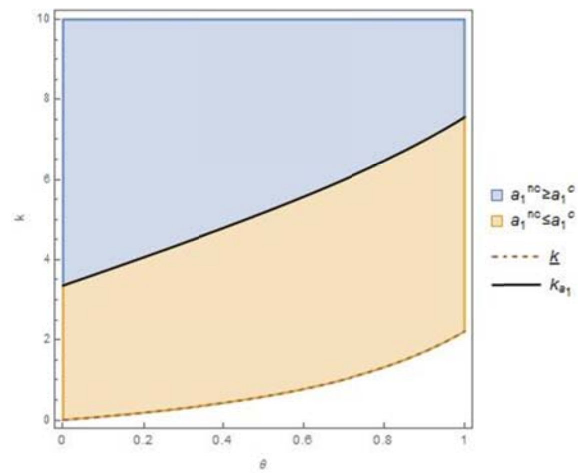


Fig. B.2. 4 Behavior of the derivative $\frac{\partial W^{nc}}{\partial \theta}$

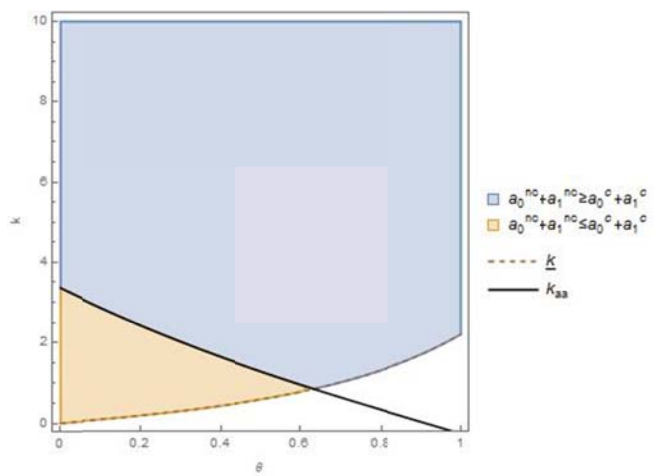
Proposition 3.8



(a) $\boldsymbol{a_0^{nc}}$ vs. $\boldsymbol{a_0^c}$



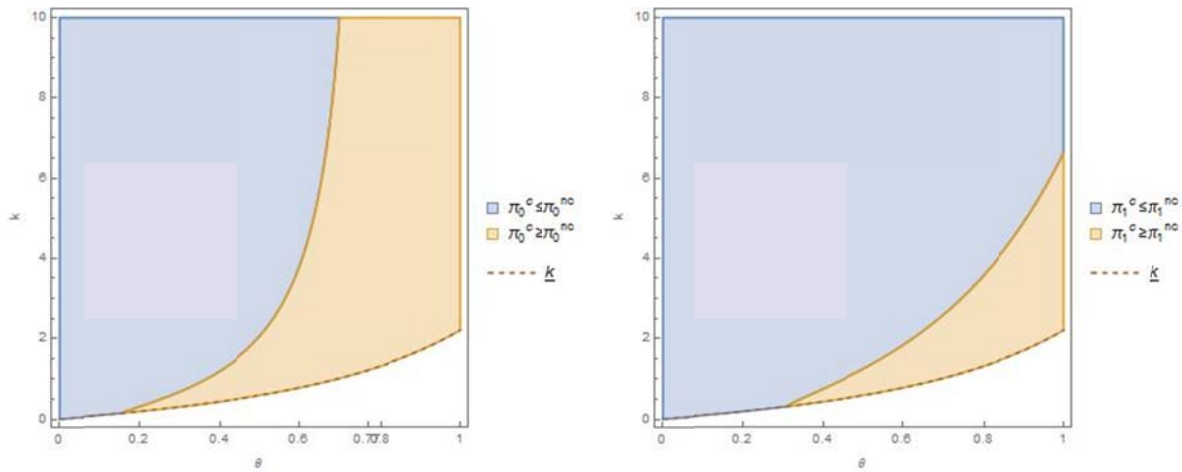
(b) $\boldsymbol{a_1^{nc}}$ vs. $\boldsymbol{a_1^c}$



(c) $\boldsymbol{a_0^{nc} + a_1^{nc}}$ vs. $\boldsymbol{a_0^c + a_1^c}$

Fig. B.2. 5 Abatement comparisons

Proposition 3.9



(a) $\boldsymbol{\pi_0^{nc}}$ vs. $\boldsymbol{\pi_0^c}$ (b) $\boldsymbol{\pi_1^{nc}}$vs. $\boldsymbol{\pi_1^c}$

Fig. B.2. 6 Profits comparisons

B.3 The Case with an Environmental CF Firm

Consider that firm $\mathbf{0}$ has the following objective function:

$$\mathrm{V}_0 = \pi_0 + \theta(\mathrm{CS} - \mathrm{ED}) \tag{1'}$$

where $\mathbf{CS} - \mathbf{ED}$ is net consumer surplus. Thus, CF firm is also conscious about the environment in a degree of $\boldsymbol{\theta}$. In the next analysis, we assume $\boldsymbol{k} = \mathbf{1}$ and compare the committed and non-committed policy regimes.

B.3.1 The committed policy regime

The equilibrium abatement efforts and outputs, the optimal emission tax and resulting marginal environmental damage are the followings:

$$t^c = \frac{147456 - 819200\theta + 1308160\theta^2 + 15360\theta^3 - 151040\theta^4 - 672\theta^5 + 441\theta^6}{\Omega} \tag{2'}$$

$$a_0^c = \frac{32(4608 + 45440\theta + 12640\theta^2 + 6440\theta^3 - 245\theta^4)}{\Omega}$$

$$a_1^c = \frac{32(4608 - 54400\theta + 54560\theta^2 - 8040\theta^3 + 35\theta^4)}{\Omega}$$

$$q_0^c = \frac{8(30720 + 38400\theta + 119040\theta^2 + 8032\theta^3 - 544\theta^4 - 273\theta^5)}{\Omega}$$

$$q_1^c = \frac{8(30720 - 145920\theta + 136960\theta^2 - 5408\theta^3 - 224\theta^4 + 147\theta^5)}{\Omega}$$

$$MED^c = \frac{16(12288 - 35840\theta - 6400\theta^2 + 1632\theta^3 + 36\theta^4 - 63\theta^5)}{\Omega}$$

$$\pi_0^c = 64\left(\frac{\begin{array}{c}1585446912 - 9673113600\theta + 10378280960\theta^2 - 1845248000\theta^3 - 852418560\theta^4 + 433249280\theta^5 \\ -142243072\theta^6 + 22831680\theta^7 + 903502400\theta^8 + 38178\theta^9 - 171549\theta^{10}\end{array}}{\Omega^2}\right)$$

$$\pi_1^c = 64\left(\frac{\begin{array}{c}1585446912 - 15335424000\theta + 18690867200\theta^2 - 11669749760\theta^3 + 5025628160\theta^4 - 982031360\theta^5 \\ -222410240\theta^6 + 134322240\theta^7 - 11105920\theta^8 - 2878260\theta^9 + 40131\theta^{10}\end{array}}{\Omega^2}\right)$$

$$W^c = \frac{16(18432 - 53760\theta + 67200\theta^2 + 3520\theta^3 - 9640\theta^4 - 63\theta^5)}{\Omega}$$

where $\boldsymbol{\Omega \equiv 1130496 - 4014408\theta + 554752\theta^2 - 50176\theta^3 - 248832\theta^4 + 672\theta^5 + 441\theta^6 > 0}$.

Proposition B.3. 1 *Under the committed policy regime,* $\boldsymbol{t^c} \lesseqgtr \boldsymbol{MED^c}$ *if* $\boldsymbol{\theta} \lesseqgtr \boldsymbol{\overline{\theta}} \approx \boldsymbol{0.733}$ *, where* $\boldsymbol{\overline{\theta}}$ *is such that* $\boldsymbol{t^c(\overline{\theta}) = MED^c(\overline{\theta})}$*.*

B.3.2 The non-committed policy regime

The equilibrium abatement efforts and outputs, the optimal emission tax and resulting marginal environmental damage are the followings:

$$a_0^{nc} = \frac{3(768 + 1080\theta - 580\theta^2 - 25\theta^3)}{2(18 - 5\theta)\Delta} \tag{3'}$$

$$a_1^{nc} = \frac{2304 - 3080\theta + 1340\theta^2 + 75\theta^3}{2(18 - 5\theta)\Delta}$$

$$q_0^{nc} = \frac{152 + 4\theta + 15\theta^2}{\Delta}$$

$$q_1^{nc} = \frac{152 - 60\theta - 5\theta^2}{\Delta}$$

$$t^{nc} = \frac{24 - 4\theta + 25\theta^2}{\Delta}$$

$$MED^{nc} = \frac{2(88 - 48\theta + 5\theta^2)}{\Delta}$$

$$\pi_0^{nc} = \frac{88501248 - 1067074560\theta + 293831040\theta^2 + 89238400\theta^3 - 52652000\theta^4 + 4660000\theta^5 - 206250\theta^6}{8(18 - 5\theta)^2\Delta^2}$$

$$\pi_1^{nc} = \frac{88501248 - 1137208320\theta + 477680000\theta^2 - 75651200\theta^3 + 20932000\theta^4 - 6040000\theta^5 - 356250\theta^6}{8(18 - 5\theta)^2\Delta^2}$$

$$W^{nc} = \frac{133788672 - 1394380800\theta + 485580160\theta^2 - 46281600\theta^3 + 5332000\theta^4 - 4530000\theta^5 - 31250\theta^6}{4(18 - 5\theta)^2\Delta^2}$$

where $\boldsymbol{\Delta \equiv 632 - 180\theta + 25\theta^2 > 0}$.

Proposition B.3. 2 *Under the non-committed policy regime,* $\boldsymbol{t^{nc} < MED^{nc}}$ *for any* $\boldsymbol{\theta \epsilon (0, 1)}$*.*

B.3.3 Comparing policy regimes

Proposition B.3. 3 $\boldsymbol{t^{nc} < t^{c}}$ *for any* $\boldsymbol{\theta \epsilon (0, 1)}$*.*

Proposition B.3. 4

1. $\boldsymbol{\pi_0^c < \pi_0^{nc}}$ *for any* $\boldsymbol{0 < \theta < \theta_{\pi_0} \approx 0.44013}$ *where* $\boldsymbol{\theta_{\pi_0}}$ *satisfies that* $\boldsymbol{\pi_0^c(\theta_{\pi_0}) = \pi_0^{nc}(\theta_{\pi_0})}$*;*

2. $\boldsymbol{\pi_1^c < \pi_1^{nc}}$ *for any* $\boldsymbol{\theta \epsilon (0, 1)}$*.*

It implies that both firms can earn simultaneously higher profits under the non-committed policy regime when the degree of concern on net consumer surplus is not too high.

Proposition B.3. 5

1. $\boldsymbol{ED^c < ED^{nc}}$ for any $\boldsymbol{\theta \epsilon (0, 1)}$;
2. $\boldsymbol{W^c > W^{nc}}$ for any $\boldsymbol{\theta \epsilon (0, 1)}$.

Therefore, the committed regime is better for any degree of concern on net consumer surplus.

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