Environmental policy and technology diffusion under imperfect competition

Vries, Frans Pieter de

Chapter 6

The Cournot model and diffusion

6.1 Introduction

The previous chapters explored the methodology for the economic modelling and the justification for adopting a Cournot framework. The discussion was mainly of a qualitative and general nature. The purpose of this chapter is to provide a more detailed discussion of the basic Cournot model and to introduce diffusion dynamics into that model. In this chapter we abstract from environmental policy. The focus is on the adoption decision of the quantity-setting Cournot firm and the diffusion process. In the next chapter restrictions on emissions are introduced and the interaction between environmental policy and diffusion of clean technology will be discussed.

Prior to illuminating the Cournot model in section 6.3, we review the assumptions of the model in section 6.2. Section 6.4 shows how technology diffusion is included and it discusses some first results. In section 6.5, a numerical example illustrates the characteristics and working of the model presented in 6.3 and 6.4. A sensitivity analysis in section 6.6 completes the illustrative example. Section 6.7 demonstrates the stability of the evolutionary equilibrium and the chapter ends with concluding remarks in section 6.8.

6.2 Assumptions and model characterization

Consider a number of firms (the individual players), all of the same size, that constitute a single industry (the population). Let $\Omega = \{1, 2, \ldots, N\}$ be the set of firms where N is the total number of firms in the market, which is assumed to be fixed. The fixedness of the industry size implies the exclusion of an entry/exit mechanism. A firm that is currently not involved in the industry cannot enter and incumbent firms cannot leave it. The argument for not including an entry/exit mechanism is due to Bresnahan and Reiss (1991) who showed that entry does not have a significant impact on the effects of competition in concentrated markets. So, the industry size is considered to be a constant.

To produce their goods, each firm $i \in \Omega$ can choose between two existing technological modes. One technology is an old 'dirty' technology, the other is a new 'clean' technology. The latter generates the output with lower emissions per unit of output. The set of available technologies represents the strategy set of the firm. The difference between the two technologies is determined by a difference in pollution intensiveness and by a difference in the cost structure. In consequence, firms are heterogeneous and the market is characterized by product differentiation. Each product manufactured with either the dirty or clean technology is sold in its own submarket. Let's discuss these three issues systematically.

First, the pollution intensiveness of the technologies. In producing the good in the traditional way with the dirty technology (implying high emissions, effluent or solid waste per unit of output), the industry under investigation generates a negative externality in terms of pollution. But a new technology is assumed to be available which produces the good with a lower level of pollution. So, both technologies generate pollution but the contribution to pollution per unit of output is, obviously, higher for the dirty technology than for the clean technology. One could think of the clean technology as a more capital intensive but less material intensive technology. Since emissions and waste generated by production are usually related to the quantities and types of materials and fuels used in the production process, less use of materials makes that the clean technology has lower emissions and waste per unit of output. This emission/output ratio is assumed to be a constant, implying that no further technological improvements in material and energy saving occurs once a technology is adopted.

Second, cost asymmetries. Firms that employ the same technology are assumed to face an identical cost structure, however, the clean technology has higher fixed costs and lower variable costs relative to the dirty technology. Higher fixed costs for the clean technology could be due to, for example, higher depreciation costs because of its higher degree of capital intensity. An interpretation of lower variable costs for the clean technology is that it is more material and energy-efficient relative to the dirty technology and therefore implies less use of materials and fuel per unit of output. Beyond the break-even point the clean technology has lowest average costs.

Third, the demand conditions for the clean and dirty product are different. Because the technologies differ in their physical attributes, i.e., the clean technology has a lower emission/output ratio than the dirty one, the products manufactured by the two types of technologies are regarded as different by consumers and are, in particular, considered to be imperfect substitutes. For instance, the product manufactured by the clean technology has an environmentally friendly image to the consumer and for that reason the consumers' willingness to pay is higher for the clean product. The above conditions imply that the market is divided into two submarkets; one for the clean product variant and one for the dirty variant. But there is indirect competition between them, i.e., an increase in the quantity of the dirty good depresses the price of the clean good and vice versa.

Given these differences between the clean and dirty technology, firms face the choice which type of technology to adopt and consequently how much to supply on the corresponding submarket. In making their choice, the firms are led by profit expectations based on profits actually earned by the firms that produce clean and dirty respectively. Moreover, once firms have chosen a specific technology they stick to it.

Firms have to decide how much to produce in order to maximize profits given their choice of technology. Firms operate in a Cournot market where they sell the profit maximizing quantity given the observed quantities of competitors that operate in the same submarket. The market determines the product prices and the profits of firms producing them.

Crucial in the model is the difference between the long-run investment decision on which type of technology to install and the short-run decision on how much to produce. Both decisions are based on actual profits but in different ways. If current profits of selling the clean product exceed current profits of selling the dirty variant, only a fraction of all firms switches from the dirty to the clean technology. Some firms stick to the old conventional technology, even though it will yield lower profits (at least for the time being). This feature reflects the inertia element, which characterizes evolutionary change. This makes diffusion of the clean technology a gradual dynamic process. However, in making decisions on output, all firms are profit maximizers in the two distinguished product markets which are characterized by immediate price adjustment to clear the markets. Firms thus maximize profits instantaneously. Interaction between firms is such that once being informed on market price elasticities and quantities set by competitors, each firm can determine its profit maximizing output quantity. The market clearing prices coordinate all decisions and establish a market equilibrium and yield corresponding profits for clean and dirty firms.

One of the questions to be investigated is how in this evolutionary game model technology diffusion behaves over time; whether it tends towards an evolutionary stable equilibrium and whether the equilibrium takes up a heterogeneous or homogeneous mode. The homogeneous industry mode comprises two situations: either all firms are of the dirty type or all are clean type firms. Consequently, the heterogeneous industry mode reflects the coexistence of the dirty and clean firms in the long-run. The number of users that comprise these two groups is endogenous.

The formal model showing the features discussed above will be introduced in section 6.3. The model serves as a benchmark case implying no account for environmental policy and therefore no regulatory constraint on emissions. Pollution is the unpriced by-product of producing output for the consumer market.

6.3 The Cournot model

This section presents a parametric Cournot model which will serve as the central device for analyzing the strategic behavior of technology adoption, diffusion and product differentiation. The effects of the various environmental policy measures on firm and industry output, pollution, product prices, costs and profits will be examined in the next chapter. A first version of the demand structure of the model was introduced by Dixit (1979) and described the duopoly case. Friedman and Fung (1996) extended this duopoly model to a N-size (two-country) oligopolistic market and transformed it into a dynamic evolutionary game model for analyzing trade effects on the internal organization of firms. This version is also adopted below; however, instead of analyzing a two country setup we focus on technology diffusion within an industry in one single country. For that purpose, we implement some changes in the cost structure. Moreover, we incorporate a pollution and environmental policy aspect, which is not part of the above studies.

6.3.1 Industry and technology structure

General

Recall the industry comprises the set of firms $\Omega = \{1, 2, \ldots, N\}$. Before a firm starts producing, each firm $i \in \Omega$ chooses one of the technological modes denoted by j. It has the choice between two types of technologies: a dirty ($j = d$) or a clean ($j = c$) one. Given the bimodal technology choice $j = d, c$, the individual firm produces a quantity $x_{i \in j}$. Firms that use a given type of production technology are identical with respect to their demand and cost conditions and have therefore identical output levels. Call x_d the output of a firm producing the dirty good and x_c the firm-level output of the clean firm. Furthermore, let k be the policy regime under consideration[1].

Product differentiation and demand

Product differentiation comes from the distinction between the two goods, based on the difference in the technological structure. What counts is that consumers perceive the two products as being different because of their different environmental characteristics. Due to product differentiation we distinguish two inverse demand functions:

$$p_d^k = \alpha_d - \beta X_d^k - \gamma X_c^k, \qquad (6.1)$$
$$p_c^k = \alpha_c - \beta X_c^k - \gamma X_d^k.$$

Equation (6.1) generates the prices for the dirty and clean product respectively. Both prices are a function of aggregate output $X_j^k = \sum_{i \in j} x_i^k$, which denotes the level of total output supplied by the firms that use technology $j = d, c$. Parameters $\beta > 0$ and $\gamma > 0$ measure the direct and cross price effects respectively. It is assumed that a firm's own output has a bigger impact on the corresponding product price than the effect of firms that act in the other submarket, i.e., $\beta > \gamma$. The assumptions imply that the demand for the clean good is more inelastic with regard to its price (the direct price elasticity) than with regard to the price of the dirty good (the indirect price elasticity). The same analogy applies to the dirty good. These features reflect that customers are attached to their type of product and that the clean and dirty good are imperfect substitutes. Moreover, the parameter assumptions $\beta, \gamma > 0$ and $\beta > \gamma$ are also necessary requirements for aggregate utility to be concave. This issue

[1] Recall that this chapter does not explore any environmental policy options and so we denote the current policy regime as laissez-faire ($k = lf$).

will be addressed in more detail in section 6.3.3. So, unless stated otherwise, from now we assume $\beta > \gamma$.

Product differentiation comes from two parameters: γ and α_j. Parameter γ relative to β determines the degree of substitutability between the two products, i.e., degree of heterogeneity. If $\gamma = 0$ the goods are independent and when $\beta > \gamma > 0$ the commodities are imperfect substitutes. We shall especially follow this latter path of analysis. A second aspect of product differentiability is measured by the intercepts α_d and α_c in equation (6.1). Conditional on the assumption of products being unidentical, a higher α_j implies an absolute advantage in demand enjoyed by the firm that employs technology j (*cf.* Dixit, 1979). In our case we presume that $\alpha_c > \alpha_d$; the clean firm has an absolute price advantage (at equal quantities) over the dirty type firm. For instance, one can imagine a price for the clean good which exceeds the price of its conventional produced substitute. So, it can be seen as a price premium on the clean good (*cf.* McGinty, 2001).

Absence from product differentiation implies the clean and dirty good being identical from the consumers' perspective. Formally this holds when the direct and cross price effects coincide ($\gamma = \beta$) and, moreover, the demand intercepts are equal ($\alpha_c = \alpha_d$). In this case the inverse demand function (6.1) reduces to:

$$p_d^k = p_c^k = \alpha - \beta(X_d^k + X_c^k), \tag{6.2}$$

representing the demand structure for the homogeneous market case.

Now define the state variable $s \in [0,1]$ as the fraction of firms in the industry that currently employ the clean technology; it reflects the degree of diffusion of clean technology. Obviously, the fraction of dirty type firms in the industry is then simply $1 - s$. For every s and at any instant, the total number of dirty firms N_d and clean type firms N_c can be found by multiplying the corresponding fractions with industry size N:

$$\begin{aligned} N_d &= (1-s)N, \\ N_c &= sN. \end{aligned} \tag{6.3}$$

These evidently sum up to industry size N. The total number of firms is a discrete number. Multiplying this with the continuous state variable s could result in a 'non-integer' number of firms[2]. Aggregate supply X_j $(j = d, c)$ can

[2] Here sN is implicitly assumed to be an integer and imposes some restrictions on the set of feasible $s \in [0,1]$. These restrictions have, however, no substantial consequences for the model (*cf.* Friedman and Fung, 1996).

now be rewritten in terms of diffusion s:

$$X_d^k = N_d x_d^k = (1-s) N x_d^k, \tag{6.4}$$
$$X_c^k = N_c x_c^k = s N x_c^k.$$

Substituting (6.4) in (6.1) we obtain the associated demand structure for the heterogeneous market as a function of the degree of diffusion s and the individual firm-level output x_j:

$$p_d^k = \alpha_d - N(\beta(1-s)x_d^k - \gamma s x_c^k), \tag{6.5}$$
$$p_c^k = \alpha_c - N(\beta s x_c^k - \gamma(1-s)x_d^k).$$

Substituting the same expression for aggregate output into (6.2), we obtain the prices in case of homogeneous products:

$$p_{d,c}^k = \alpha - \beta N((1-s)x_d^k + s x_c^k), \tag{6.6}$$

which characterizes goods being identical from the consumers' perspective. As a next step, we will now examine the cost structure of the two goods in more detail.

Costs and net absolute advantage

Assume total costs of production for a firm employing technology $j = d, c$, and which is subject to policy regime k, faces a linear structure according to:

$$c_j^k = \mu_j + \vartheta_j x_j^k, \tag{6.7}$$

where $\mu_j > 0$ is total fixed costs and $\vartheta_j > 0$ the average variable production cost. The cost function is continuous and non-decreasing. We assume for simplicity that total variable costs are proportional to the level of output. Above we argued that, due to reasons of energy-efficiency, the clean technology faces lower constant average variable costs relative to the dirty technology[3]: $\vartheta_c < \vartheta_d$. On the other hand, the clean technology embodies higher fixed (sunk) costs, i.e., $\mu_c > \mu_d$. It should be noted that the cost structure reflects increasing returns for both technologies, but it is most prominent in the clean technology.

Recall that the intercepts α_j of the price functions (6.1) can reflect an absolute advantage in demand. Because this advantage is not adjusted for

[3] This assumption is different from Requate (1998) in which the cleaner technology incurs higher marginal costs.

variable costs it is a *gross* measure. The *net* absolute advantage can be derived by relating α_j to the cost function (6.7). Following Dixit (1979) define:

$$\theta_j = \alpha_j - \vartheta_j > 0, \tag{6.8}$$

which reflects the net absolute advantage for a technology j-mode firm. Given the above assumed inequalities of $\alpha_c > \alpha_d$ and $\vartheta_c < \vartheta_d$, it directly follows that $\theta_c > \theta_d$, i.e., at the margin the clean type firm exhibits a net absolute advantage over the dirty type firm.

Pollution

A firm adopting technology j generates a negative externality in terms of emissions e_j. We assume a linear relationship between emissions and production. The emission function of a j-mode firm under policy regime k equals:

$$e_j^k = \zeta_j x_j^k, \tag{6.9}$$

where ζ_j is the emission/output ratio, i.e., the amount of emissions per unit of production. It is easy to see that marginal emissions are exactly equal to this ratio. By definition, the clean technology generates lower emissions per unit of production than the dirty technology and so we face the inequality $\zeta_c < \zeta_d$. The potential attainable level of emission reduction is then $(\zeta_c - \zeta_d)/\zeta_d \times 100\%$.

6.3.2 The output decision of a firm

There are two distinct decisions a firm has to make. They are of a short-run and long-run nature. The long-run decision implies the choice of the production technology. This issue will be examined in the next section and brings us therefore first to the short-run decision making problem. Because firms are assumed to be profit maximizers, they choose the optimal level of output given their own technology choice and given the distribution of clean and dirty technology across the industry. So, firms first choose technologies and then corresponding outputs that maximize short-run profits. Crucial here is the state variable $s \in [0, 1]$ reflecting the degree of diffusion of clean technology. A firm's output decision first of all depends on the choice of technology which is conditional on the distribution of technology in the industry.

For now assume that when a firm has adopted technology j, it chooses a non-negative output level x_j that maximizes profits π_j by considering the output decisions of other firms as given. That is:

$$\max_{x_j} \pi_j = p_j x_j - c_j. \tag{6.10}$$

Substituting (6.1) and (6.7) into (6.10) gives the profit functions to be maximized by the firms applying the clean and dirty technology respectively:

$$\max_{x_d} \pi_d = (\alpha_d - \beta(\widehat{X}_d + x_d) - \gamma X_c)x_d - \mu_d - \vartheta_d x_d, \tag{6.11}$$
$$\max_{x_c} \pi_c = (\alpha_c - \beta(\widehat{X}_c + x_c) - \gamma X_d)x_c - \mu_c - \vartheta_c x_c,$$

where

$$\widehat{X}_j = X_j - x_j, \tag{6.12}$$

denotes total output of all other firms producing the same product given a firm supplies x_j. Rewriting (6.11) gives us an expression for profits with the net absolute advantage term θ_j as given in (6.8):

$$\max_{x_d} \pi_d = (\theta_d - \beta(\widehat{X}_d + x_d) - \gamma X_c)x_d - \mu_d, \tag{6.13}$$
$$\max_{x_c} \pi_c = (\theta_c - \beta(\widehat{X}_c + x_c) - \gamma X_d)x_c - \mu_c.$$

The first-order conditions for this maximization problem are:

$$\frac{\partial \pi_d}{\partial x_d} = \theta_d - \beta(\widehat{X}_d + x_d) - \gamma X_c - \beta x_d = 0, \tag{6.14}$$
$$\frac{\partial \pi_c}{\partial x_c} = \theta_c - \beta(\widehat{X}_c + x_c) - \gamma X_d - \beta x_c = 0,$$

and coincide with the implicit reaction functions of the Cournot model. Substituting (6.4) into (6.14), taking into account that the state of diffusion s is given when firms determine their output decision, the simultaneous solution to (6.14) yields the following optimal Cournot-Nash output levels for the laissez faire regime:

$$x_d = \frac{\beta(sN+1)\theta_d - \gamma sN\theta_c}{\Theta}, \tag{6.15}$$
$$x_c = \frac{\gamma(s-1)N\theta_d - \beta((s-1)N-1)\theta_c}{\Theta},$$

where:

$$\Theta = \beta^2(N+1) - (s-1)sN^2(\beta^2 - \gamma^2) > 0. \tag{6.16}$$

The Cournot-Nash firm-level output levels in (6.15) are nonlinear in diffusion s. Due to this nonlinear structure $dx_j/ds \gtrless 0$ ($j = d, c$). However, for reasons of simplicity, we assume that $dx_c/ds < 0$ and $dx_d/ds > 0$. The intuition behind this is as follows. When more and more firms switch to the clean production mode (diffusion of clean technology increases), the equilibrium output levels will be lower since firms have to share the market with more direct competitors producing the same good. The same intuition holds for firms generating dirty goods. When more firms enter the dirty product market, the lower the equilibrium output levels of the dirty goods, implying that it is *increasing* in diffusion s.

The optimal Cournot-Nash output levels in (6.15) are the short-run quantities, i.e., the combination of outputs such that no firm can increase its profits by changing its output alone. Substituting the output levels (6.15) in (6.10) yields the firm-level profits for dirty and clean production respectively. A short-cut representation of the profit function (6.10) is[4]:

$$\pi_j = \beta x_j^2 - \mu_j. \tag{6.17}$$

Since production x_j is a function of diffusion s, it is straightforward to see that the relative profitability of the two technologies depends on the state variable s as well as external 'environmental' variables such as demand and cost conditions. In consequence, the setup of the model is now as such that all the variables (prices, outputs, costs, profits and pollution) are endogenous to the degree of diffusion s. Furthermore, because $dx_d/ds > 0$ and $dx_c/ds < 0$, it directly follows that $d\pi_d/ds > 0$ and $d\pi_c/ds < 0$; that is, clean firm profits are decreasing in the fraction of clean type users; dirty firm profits are increasing in the diffusion of clean technology.

6.3.3 Consumer market and welfare

As usual in the Cournot model, there is perfect competition among consumers at the demand side of the market, i.e., consumers act as price takers. Next to that, there is immediate price adjustment such that markets are cleared. In other words, the model assumes that all output supplied on one of the two submarkets will be sold.

The preference relationship can be expressed by an aggregate utility function U of the following form:

$$U = V + m, \tag{6.18}$$

where m is numeraire income and

$$V = \sum_{j=d,c} \alpha_j X_j - \frac{1}{2}\left(\beta \sum_{j=d,c} X_j^2 + 2\gamma X_d X_c\right). \tag{6.19}$$

[4] See appendix 6A for derivation.

It is assumed that aggregate utility is concave and separable in income m. The concavity condition is met when $\beta > 0$ and $\beta > \gamma$ and insures the heterogenous character of the market as outlined in the discussion on the market structure. From (6.18) one can derive the demand structure given in (6.1; the inverse demand functions for each product variant given in (6.1) are the partial derivatives of aggregate utility U, i.e., $p_j = \partial U / \partial X_j$ $(j = d, c)$.

Fung (1988) shows that consumer surplus CS for the above utility structure can be derived without facing problems of income effects. For this specific utility function he shows that consumer surplus equals:

$$\begin{aligned} CS &= V - p_d X_d - p_c X_c \\ &= \frac{1}{2}\beta\left(X_d^2 + X_c^2\right) + \gamma X_d X_c. \end{aligned} \tag{6.20}$$

Producer surplus PS as the other component of welfare, is simply the sum of *all* clean firm profits Π_c and *all* dirty firm profits Π_d in the industry:

$$\begin{aligned} PS &= \Pi_d + \Pi_c \\ &= (1 - s)N\pi_d + sN\pi_c. \end{aligned} \tag{6.21}$$

As usual, summation of CS and PS gives the level of total welfare W:

$$W = CS + PS. \tag{6.22}$$

One may wonder why welfare is not adjusted for pollution, i.e., pollution is a negative externality and would probably reduce welfare. However, we choose not to adjust for this for the following reason. Pollution usually has the characteristic of a public bad. Therefore, the individual consumer can neglect the impact of higher environmental damage, caused by emissions in producing the good, on his own welfare. That is why we construct individual and aggregate demand functions which do not contain an explicit demand for an environmental quality component. Environmental demand comes, however, implicitly and indirectly through the price premium on clean goods relative to dirty goods. Next to that, consumers can express their preference for environmental quality when they bring out their political vote. In the next chapter, environmental preferences will be brought in in the form of government restrictions on industry emissions, for example in terms of an overall industry emission target. Maximizing welfare under the restriction that total industry emissions remain below these policy targets, one obtains a shadow price for emissions that expresses the scarcity of 'environmental space'. This shadow price coincides with the permit price under a tradable permit system with perfect competition on the permit market. Besides, given regulators do not have perfect information on costs and benefits of abatement, it is hard to choose the optimal abatement levels in advance of setting the appropriate policy. In reality, emission goals are chosen rather arbitrarily hence making an efficiency analysis from the control authority's point of view quite difficult.

6.4 Technology diffusion

This section outlines the dynamics on which technology switching is based. We introduced the state variable s reflecting the degree of clean technology diffusion, i.e., the fraction of clean type firms in the industry. We are especially interested in the dynamic behavior of this diffusion process and the long-run outcome, i.e., the extent of penetration of clean type firms in the industry. Two main questions are distinguished. First, how far will penetration of the clean firms go, i.e., what is the equilibrium level of diffusion? Second, how will this equilibrium be reached? The latter question implies that we have to determine the qualitative behavior of the diffusion process. We first focus on the dynamic specification of the diffusion process (subsection 6.4.1). Then we turn to the calculation of the long-run equilibrium degree of diffusion (subsection 6.4.2). The section concludes with comparative statics exercises (subsection 6.4.3).

6.4.1 Dynamics

In chapter two it was argued that the evolutionary adjustment dynamic should embody inertia. In our model, the evolutionary adjustment process that drives the change in the diffusion of clean technology s (and so also the diffusion of dirty technology $1 - s$), is the relative profitability of the two alternative technologies. The technology that yields a higher payoff in terms of profits will displace the lower payoff technology. So, only differences in payoff matter. Evidently, firms have no incentive to switch technologies when the payoffs for both technologies are equal.

For all policy regimes k, define the profit differential as:

$$\Delta\pi^k = \pi_c^k - \pi_d^k. \tag{6.23}$$

From (6.23) it directly follows that when $\Delta\pi^k > (<)\ 0$, the clean technology yields a higher (lower) profit level than the dirty technology. Following a continuous time deterministic framework, for every policy regime k and any initial state $s^k(0) = s_0^k$, the adjustment dynamic for technology switching can be expressed as:

$$\dot{s}^k \equiv \frac{ds^k}{dt} = H^k(s^k, z^k), \tag{6.24}$$

where H^k is a dynamic which depends on the state of diffusion s^k and the external environment summarized by the vector z^k. Friedman (1991) introduces the term compatibility to express the dynamic H^k in terms of the game payoffs. Compatibility basically incorporates the idea that fitter strategies displace less fit strategies. In our model, the payoffs are expressed in terms of profits under the two technology regimes. The fitter strategy (technology) is the strategy (technology) which yields higher profits. Then compatibility implies that when the clean (dirty) technology yields higher (lower) profits than the dirty (clean) technology, it displaces the dirty (clean) technology:

$$\dot{s}^k \lesseqgtr 0 \Longleftrightarrow \Delta\pi^k \lesseqgtr 0. \tag{6.25}$$

In this specific economic model, $H^k(s^k, z^k) = \Delta\pi^k(s^k, z^k)$. The profit differential depends on diffusion s^k because output levels and hence profits depend on s^k. In our model, the vector z^k comprises demand, cost and policy conditions. The formal conditions for the dynamic H^k to be compatible with $\Delta\pi^k$ are (Friedman, 1998):

1. $sign\ H^k(s^k, z^k) = sign\ \Delta\pi^k(s^k, z^k)$;
2. $\left|H^k(s^k, z^k)\right| \geq \varepsilon \left|\Delta\pi^k(s^k, z^k)\right|$ for some $\varepsilon > 0$;
3. $\Delta\pi^k(0, z^k) < 0 \Longrightarrow H^k(0, z^k) = 0$ and $\Delta\pi^k(1, z^k) > 0 \Longrightarrow H^k(1, z^k) = 0$.

The first condition covers the idea that the technology which yields higher profits becomes more prevalent. If the sign of the dynamic H^k equals the sign of the profit differential, the dynamics of diffusion will change into the corresponding direction. In our case, if the sign of the profit differential is positive, the clean type firms become more prevalent since more firms adopt the clean technology because they expect to make more profits with clean production. The reverse case applies when the sign of the adjustment dynamic is negative. Conditions 2 and 3 are solely for technical reasons. Condition 2 ensures that the adjustment dynamics does not become too slow; condition 3 implies that no technology claims more than 100% of all firms participating in the industry. The conditions are all satisfied for the compatible dynamic $\Delta\pi^k$ (*cf.* Friedman and Fung, 1996).

More specifically, given that compatibility holds, the dynamic H^k can be represented by the profit differential (6.23). Equation (6.24) then becomes:

$$\dot{s}^k = \Delta\pi^k = \pi_c^k - \pi_d^k. \tag{6.26}$$

Equation (6.26) expresses the idea that when the profits of using the clean technology exceed profits of firms applying the dirty technology, the fraction of clean type firms will increase[5]. That is, the change in the proportions of clean and dirty technology users, is conditional on the change of the profit differential.

6.4.2 Short-run versus long-run equilibrium

The short-run equilibrium is determined by the levels of output that maximize firm profits. It is of a Cournot-Nash kind. Recall one of our assumptions that prior to deciding how much to produce, a firm has already chosen its production technology. This implies that for each value of diffusion s, the corresponding Cournot market equilibrium can be calculated; that is, outputs, prices and profits for both technologies. Consequently, the profit differential can be expressed as a function of s. The question is: to what state of technology diffusion will the industry eventually converge in the long-run? We therefore have to focus explicitly on the diffusion dynamic (6.26). Let's examine this more carefully.

From (6.23) and (6.26) we see that firms are indifferent between the two technologies when the profits of clean and dirty firms are equal, i.e., $\pi_c^k = \pi_d^k \implies \dot{s}^k = \Delta\pi^k = 0$. The state s for which this holds is then a Nash equilibrium. Because this applies to all policy regimes k, let's, for convenience, suppress this superscript. Recall however that this chapter abstracts from environmental policy and so the derivation of the long-run equilibrium reflects the laissez faire situation. More specifically, substituting (6.17) in (6.23) and rewriting gives that firms are indifferent if:

$$\beta x_c^2 - \mu_c = \beta x_d^2 - \mu_d. \tag{6.27}$$

Now assume for simplicity zero fixed costs for both technologies ($\mu_d = \mu_c = 0$)[6].

[5] The speed of clean technology diffusion depends on how big the difference in profits between the two technologies is. This is measured by the absolute value of the change in diffusion s, i.e., $|\dot{s}|$.

[6] In section 6.7 we show that this is not a critical assumption and it does not affect the *qualitative* behavior of the various functional relationships.

Moreover, since outputs are positive, equation (6.27) can be written as:

$$x_c = x_d. \tag{6.28}$$

Substitution of the optimal laissez faire Cournot-Nash quantities according to (6.15) in (6.28) and solving for s, yields the following analytical expression for the interior laissez faire Nash equilibrium at which firms are indifferent between the clean and dirty technology:

$$\tilde{s}^{lf} = \frac{\beta(N+1)\theta_c - (\beta+\gamma N)\theta_d}{(\beta-\gamma)N(\theta_d+\theta_c)}, \tag{6.29}$$

where $\tilde{s}^{lf}$ is truncated below at 0 and above at 1. We shall examine the long-run equilibrium (6.29) more carefully now by conducting some comparative statics[7].

6.4.3 Comparative statics

For convenience we suppress superscript $k = lf$. First, the effect on the long-run equilibrium due to changes in the net absolute advantages θ_j:

$$\frac{\partial \tilde{s}}{\partial \theta_d} = -\frac{(\beta(N+2)+\gamma N)\theta_c}{N(\beta-\gamma)(\theta_c+\theta_d)} < 0, \tag{6.30a}$$

$$\frac{\partial \tilde{s}}{\partial \theta_c} = \frac{(\beta(N+2)+\gamma N)\theta_d}{N(\beta-\gamma)(\theta_c+\theta_d)} > 0. \tag{6.30b}$$

In (6.30), the denominator $N(\beta-\gamma)(\theta_c+\theta_d) > 0$ since $\beta > \gamma$. As (6.30a) shows, the equilibrium outcome declines when the net absolute advantage of the dirty firm increases. This makes sense since having a net absolute advantage over the clean firm implies that more firms initially would stick to the dirty technology, i.e., the incentive effect to switch from dirty to clean is lower when the dirty type firm faces this initial advantage. The reverse applies when the clean firm faces a net absolute advantage over the dirty firm ($\theta_c > \theta_d$). A further increase in θ_c implies an even stronger initial effect to switch from clean to dirty. Hence the positive effect (6.30b). Recall the explicit definition of the net absolute advantage of a firm employing technology $j = d, c$ as given in (6.8). Based on this definition it follows automatically that an increase in θ_j can be due to either an increase in the absolute demand α_j or a decline in the variable production costs ϑ_j. Subsequently, the lower ϑ_c is relative to ϑ_d, or

[7] To get somewhat ahead of the discussion on the stability of this equilibrium in subsection 6.7, we note that for every policy regime k, the interior solution $\tilde{s}^k$ is stable (unstable) if $d\Delta\pi^k/d\tilde{s}^k < (>)\ 0$ (*cf.* Friedman and Fung, 1996).

the higher α_c is relative to α_d, the higher is the net absolute advantage of the clean firm θ_c relative to the net absolute advantage of the dirty firm θ_d. When this applies and given the comparative statics result of (6.30), we can state that the penetration of clean technology in the long-run will then be higher. What happens to the equilibrium distribution when neither firm type has an absolute advantage, that is, $\theta_d = \theta_c$? Putting this into (6.29) yields an equal segregation of the industry implying a state $\tilde{s} = 1/2$ (proof in appendix 6A). In the long-run, 50% of the firms will adopt the dirty technology and 50% will adopt the clean technology.

Recall that product differentiation comes from the parameters α_j and γ. Above we analyzed the effect of changes in the demand intercept α_j. With respect to a ceteris paribus increase in the differentiation parameter measured by the cross-price effect γ, we find:

$$\frac{\partial \tilde{s}}{\partial \gamma} = \frac{\beta(N+1)(\theta_c - \theta_d)}{N(\beta-\gamma)^2(\theta_c+\theta_d)} \lesseqgtr 0 \Longleftrightarrow \theta_c \lesseqgtr \theta_d, \tag{6.31}$$

provided that $\beta > \gamma$. The result says that when the clean firm has an absolute advantage over the dirty firm, an increase in the cross-price effect γ, i.e., a higher degree of product substitutability, results in a further penetration of clean technology. The profits under the clean technology mode thus remain higher for a larger range of s.

Given the outcome of (6.31), it could be expected that an increase in the direct price effect β would generate the opposite result. This is indeed what we find:

$$\frac{\partial \tilde{s}}{\partial \beta} = -\frac{\gamma(N+1)(\theta_c - \theta_d)}{N(\beta-\gamma)^2(\theta_c+\theta_d)} \lesseqgtr 0 \Longleftrightarrow \theta_c \gtreqless \theta_d. \tag{6.32}$$

Under the assumption that the clean firm faces a net absolute advantage relative to the dirty firm, an increase in β would yield a lower equilibrium degree of diffusion. Note that a higher β implies a lower (absolute value of) direct price elasticity. The intuition here is that a less elastic demand for clean goods is an incentive for clean firms to supply less in order to fetch higher prices. Such behavior depresses actual demand for clean products, leaving more opportunities for selling the dirty product. Apparently, the number of firms switching to the clean technology is also lower. On the other hand, when the dirty firm is the one with the net absolute advantage, an increase in the direct price effect β induces more firms to adopt the clean technology in the long-run.

Comparative statics with respect to the industry size N show that:

$$\frac{\partial \tilde{s}}{\partial N} = \frac{\beta(\theta_d - \theta_c)}{(\beta-\gamma)N^2(\theta_d+\theta_c)} \lesseqgtr 0 \Longleftrightarrow \theta_c \gtreqless \theta_d, \tag{6.33}$$

again given $\beta > \gamma$. From the numerator it is easy to see that $\partial\tilde{s}/\partial N = 0$ if either $\beta = 0$ or $\theta_d = \theta_c$. Although the thesis especially deals with environmental policy and diffusion dynamics in imperfect competitive markets, the limit case in terms of the industry size N is easy to derive. As the industry size gets infinitely large, reflecting a perfect competitive market, the long-run diffusion equilibrium equals:

$$\lim_{N\to\infty} \tilde{s} = \frac{\beta(\theta_d - \theta_c)}{(\beta-\gamma)(\theta_d + \theta_c)}, \tag{6.34}$$

which is truncated below at $s = 0$ and above $s = 1$. Up till now, most aspects of the theoretical model have been examined. We will now provide a numerical illustration in order to get an impression of the behavior of the model.

6.5 A numerical example

So far, we have outlined the basic model and expressed the output levels x_j of the profit-maximizing firms as a function of diffusion s. Hence prices p_j, costs c_j, profits π_j and pollution e_j are also dependent on s. In this section we present a numerical example based on the following parameter assumptions: $N = 8, \alpha_d = 190, \alpha_c = 200, \beta = 1.5, \gamma = 1, \vartheta_d = 20, \vartheta_c = 12, \zeta_d = 0.6, \zeta_c = 0.4$. The values show a price premium on the clean good ($\alpha_d < \alpha_c$) and a direct price effect exceeding the cross-price effect ($\beta > \gamma$): the goods are imperfect substitutes. The variable costs for the clean technology are lower than for the dirty technology ($\vartheta_d > \vartheta_c$) and the emission output ratio for the clean technology is also lower compared to dirty technology ($\zeta_d > \zeta_c$).

Figure 6.1 illustrates the dirty and clean firm-level Cournot-Nash quantities as a function of diffusion s. It shows that for relatively low s (before the intersection point where $x_c = x_d$) $x_c > x_d$. After the intersection point $x_c < x_d$. The demand faced by the individual firm is larger when the number of rivals in its type is lower, given the market demand function for clean and dirty products . Therefore, the profit maximizing output will be higher. Because production costs c_j, profits π_j and firm-level emissions e_j are proportional to x_j (see equation (6.7), (6.17) and (6.9) respectively), these variables behave qualitatively in the same way as illustrated in figure 6.1. So the costs, profits and firm-level emissions of a clean firm are decreasing in s and vice versa for the corresponding dirty firm variables.

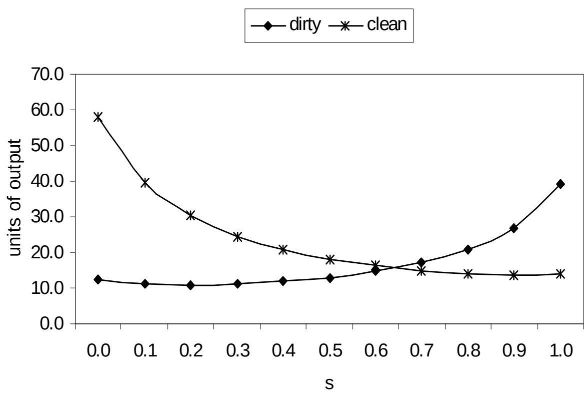

Figure 6.1: *Cournot-Nash firm-level quantities.*

Given the values of x_d and x_c, one can construct the profit differential $\Delta\pi = \pi_c - \pi_d$. This is shown in figure 6.2. The profit differential is zero ($\pi_c = \pi_d$) at $\tilde{s} = 0.645$. It is the state of diffusion where firms are indifferent between the two technologies. Moreover, figure 6.2 indicates that for $s < (>)$ $\tilde{s}$ the profit differential is positive (negative). At diffusion states $s < \tilde{s}$, there is a tendency to switch from dirty to clean due to the positive profit differential (s goes up), whereas firms switch from clean to dirty for $s > \tilde{s}$ (s goes down). Therefore, $\tilde{s} = 0.645$ is locally asymptotically stable and is the evolutionary equilibrium. It means that in this particular example there will be a long-run stable mixture of 64.5% of the firms being clean and 35.5% being dirty, reflecting a situation where both the dirty and clean product types coexist. This particular case shows that the dirty product type is not completely wiped out by its clean type substitute.

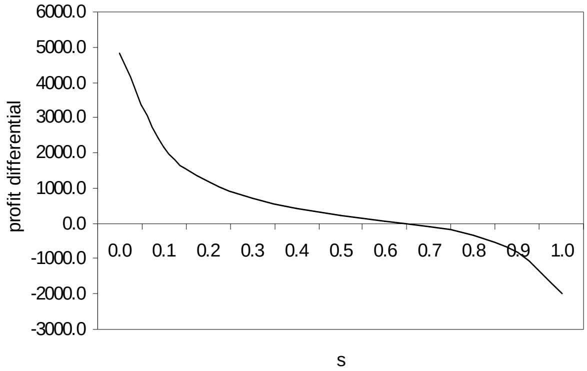

Figure 6.2: *Profit differential.*

The higher demand and profits of the clean firm relative to the dirty firm in the early stage of the diffusion process goes hand in hand with a high price for its product. As can be seen from figure 6.1, the output level of the clean firm is high compared to the dirty firm for relatively low diffusion states s. Because total costs vary proportionally with production, these must also be higher for the clean firm relative to the dirty firm. This adverse cost effect for the clean firm must therefore be compensated by higher revenues in order to generate a positive profit differential at these states. Due to a high demand for clean products when diffusion is low, the price for the clean good should be high (enough) to offset the high total cost level of clean firm. Figure 6.3 sketches the price development for the clean and dirty product as a function of diffusion. For the above numerical values, the prices are equal at diffusion state $s = 0.495$. Figure 6.3 shows that $p_c > (<)\ p_d$ for $s < (>)\ 0.495$. The higher value of the clean product price p_c relative to p_d in the early stage of diffusion, is the result of a limited aggregate supply of clean products as only few firms have adopted the clean technology. Therefore, one can fetch a relatively high price for the clean product when s is low. An increase of diffusion s reduces the scarcity of the clean product; for s very high demand is satiated and the market position in terms of price for the dirty product improves. So, a market shared with only few competitors leads to the possibility to fetch a higher price. In the equilibrium state $\tilde{s} = 0.645$, $p_c < p_d$ because clean firms face lower variable costs.

Recall the study by Moraga-González and Padrón-Fumero (2002) who explicitly assume that consumers are willing to pay more for the clean good. However, if we explicitly take the diffusion process into account, the willingness to pay for both the dirty and clean good becomes endogenous. Our analysis then shows that consumers do not always want to pay more for the clean good. Such a situation may already occur before the system has reached its final diffusion equilibrium $\tilde{s}$, as figure 6.3 shows. The willingness to pay for the clean good is lower than the willingness to pay for the dirty good for diffusion states $0.495 < s < 1$.

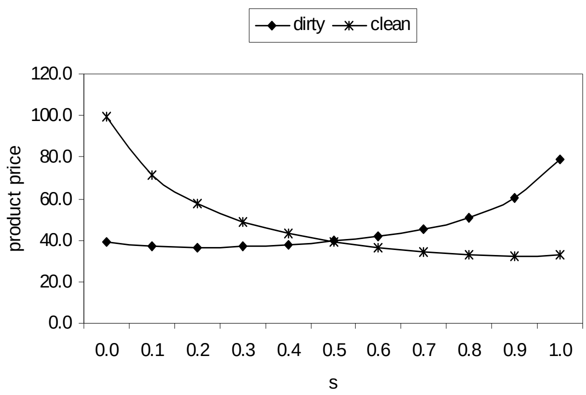

Figure 6.3: *Product prices.*

Plotting the aggregate volume of industry emissions against diffusion, gives the result as in figure 6.4. Striking is the fact that the total level of emissions is (slightly) increasing in the first stage of the diffusion process. In this example, industry emissions are at a maximum at $s = 0.194$. After this point one observes a fall in the aggregate volume of emissions. In the equilibrium degree of diffusion $\tilde{s} = 0.645$, the clean firms in the industry contribute most to pollution: $E_c = 32.1$ (54.7%) and $E_d = 26.6$ (45.3%). The average volume of emissions over the whole diffusion process $s \in [0, 1]$ is 57.7.

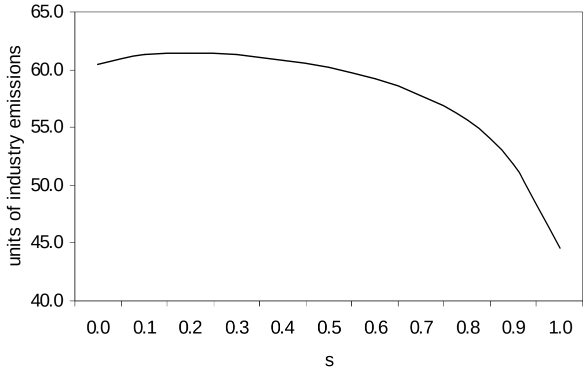

Figure 6.4: *Industry emissions.*

To gain insight into why industry emissions tend to increase in the early stage of the diffusion path, we plotted total industry output against diffusion s in figure 6.5. The figure also distinguishes the aggregate volumes of clean output X_c and dirty output X_d.

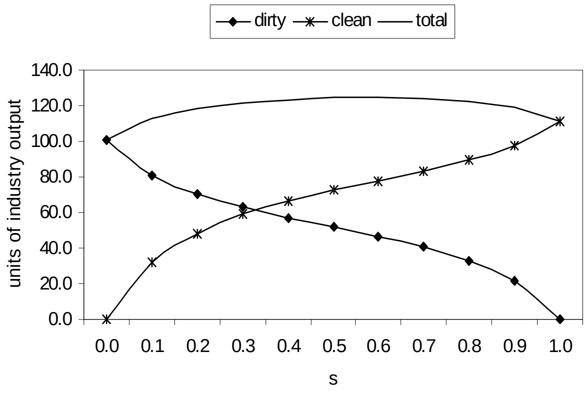

Figure 6.5: *Aggregate clean, dirty and industry output.*

The volume of industrial output increases as diffusion evolves from $s = 0$. In other words, the total amount of clean output X_c increases more than the total quantity of dirty output X_d decreases. The change in emissions (see figure 6.4) is the result of two effects: a *production effect* and a *substitution effect*. In the early stage of diffusion the production effect dominates the substitution effect of switching from the dirty to the clean technology with a lower emission/output ratio. One can conclude from this that the introduction and diffusion of clean technology under a laissez faire policy can cause a deterioration of environmental quality. Moreover, figure 6.5 indicates that for relatively low values of s, aggregate clean industry output X_c is low, implying a relative scarcity of the clean good. This scarcity results in a relatively high price p_c (see figure 6.3). As stated before, sharing a market with only a single or few competitors leads to the possibility to charge a higher price. Alternatively, the price for the dirty good p_d is high for low diffusion states because a relatively large number of firms supply this dirty product variant, but at the same time do not produce on a large scale at the individual firm-level.

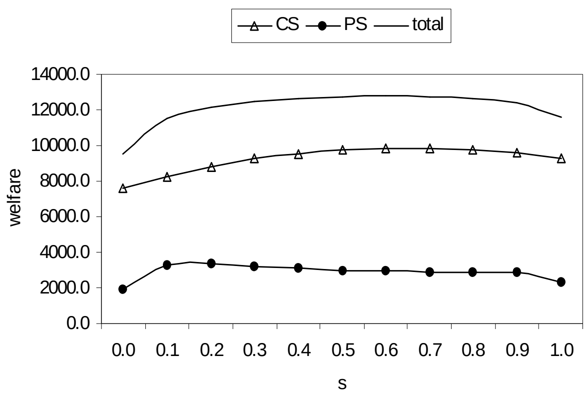

Figure 6.6: *Consumer surplus, producer surplus and total welfare.*

Based on aggregate output, total welfare, consumer surplus and producer surplus can be calculated. Figure 6.6 gives an impression of this. In the neighborhood of the evolutionary equilibrium $\tilde{s} = 0.645$, consumer surplus is near a maximum and is due to the combination of low prices and high outputs around this state (*cf.* McGinty, 2001). Producer surplus seems at maximum levels near one of the corner states. Here the combined prices are relatively high. Combining consumer and producer surplus yields total welfare, which behaves according to the behavior of industry output X (see figure 6.5).

6.6 Sensitivity analysis

As a next step we will check the robustness of the previous numerical results by analyzing the effects of a changing market structure. The analysis in this thesis centers around markets of imperfect competition with heterogeneous products. Such a market structure implies different demand functions for the dirty and clean product variant with a direct price effect β exceeding the cross-price effect γ [*cf.* equation (6.1)]. To explore the effects of a changing market structure on the most important variables, we let γ vary on the interval $[0, \beta]$. By doing so, we can see how the model behaves as the market structure evolves from a relatively strong differentiated market (γ is low) to a mode featuring a relatively weak degree of product differentiation (γ is high). In the light of the numerical values $\gamma \in [0, 1.5]$; i.e., the market evolves from products being imperfect substitutes to perfect substitutes. By letting γ increase, in fact, implies that the environmental preference becomes less manifest, i.e., the customer binding for the dirty product becomes relatively stronger. As above, we maintain the price premium on the clean good $(\alpha_c > \alpha_d)$[8]. So, we follow the route where the environmental or price premiums on the goods are different, but where product substitutability evolves from imperfect to perfect.

Figure 6.7 shows the firm-level supply of the Cournot-Nash quantities x_d (left panel) and x_c (right panel). When the products become closer substitutes ($\gamma \to 1.5$), diffusion has less impact on the quantities produced by the two firm types. This is evidently due to the fact that the products are more identical and the two submarkets (clean and dirty) largely coincide. Subsequently, the product prices p_j (which we have not pictured here) follow the same behavior as the firm-level quantities as depicted in figure 6.7. When both diffusion s and γ are relatively low, the aggregate supply of the clean good X_c is limited due to the few firms that employ the clean technology making $p_c > p_d$. The reverse holds when diffusion is high (but γ still low). Then $p_c < p_d$ because of the limited aggregate supply of dirty products X_d. The difference between the

[8] We conducted a sensitivity analysis with $\alpha_d = \alpha_c$, but this yielded no qualitative differences with $\alpha_d < \alpha_c$.

Cournot-Nash quantities and hence prices become less sensitive to changes in the level diffusion as product substitutability increases.

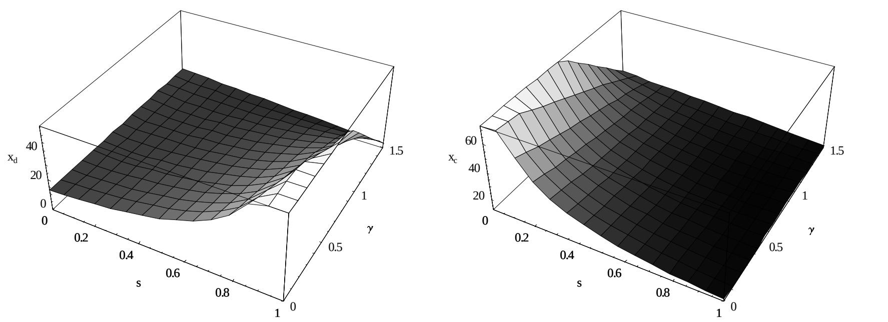

Figure 6.7: *Cournot-Nash firm-level quantities as function of diffusion and cross-price parameter γ.*

Based on firm-level output, the profit differential can be constructed as depicted in figure 6.8. The rationale above can also be applied to the profit differential. When the products become closer substitutes, the difference in the quantities supplied and difference in product prices vanishes hence making the profit differential also smaller (given s).

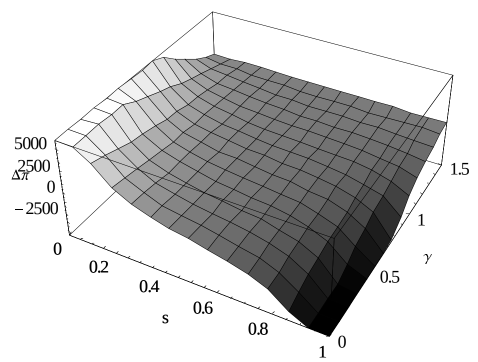

Figure 6.8: *Profit differential as function of diffusion and cross-price parameter γ.*

In figure 6.9 we see the evolution of the aggregate dirty output X_d (left panel) and aggregate clean output X_c (right panel) as a function of s and γ. Variable X_d is decreasing and X_c increasing in s for all $\gamma \in [0, 1.5]$. So, a changing market structure in terms of a change in product substitutability does not seem to generate a significant change in the aggregate supply of both product variants.

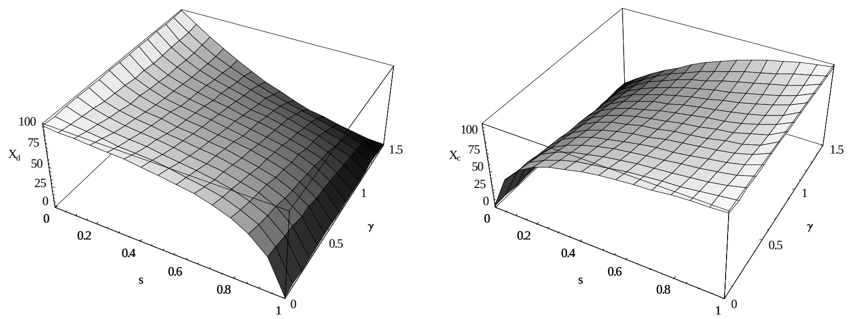

Figure 6.9: *Total dirty and clean output as function of diffusion and cross-price parameter γ.*

Summation of X_d and X_c yields industry output X as shown in figure 6.10. Diffusion has lower impact on the development of X when products become closer substitutes. For example, consider the situation where γ is low. Then, as we have argued before, total output increases in the first stage of diffusion and starts to fall in the second stage. This effect in the first stage is due to the fact that the increase in X_c is bigger than the decrease in X_d. Starting from $s = 1$ (and γ still low) the reverse holds, i.e., the increase in X_d exceeds the increase of X_c. By taking a closer look at figure 6.9 reveals that this is true. An increase in the product substitutability shows that these two effects vanish.

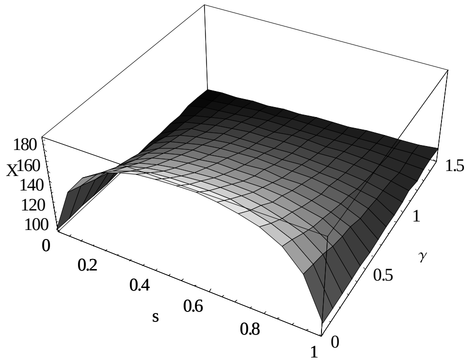

Figure 6.10: *Industry output as function of diffusion and cross-price parameter* γ.

Multiplying X_d and X_c with the corresponding emission coefficients ζ_d and ζ_c respectively and adding up yields the industry volume of emissions E as pictured in figure 6.11. Higher product substitutability implies that the effect of an increase in industry emissions in the first stage of diffusion disappears.

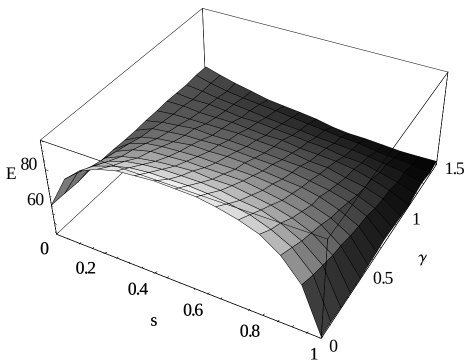

Figure 6.11: *Industry emissions as function of diffusion and cross-price parameter* γ.

Finally, a look at welfare. Figure 6.12 shows how consumer surplus CS (left panel) and producer surplus PS (right panel) changes as a function of s and γ. For low γ, consumer surplus first increases in s and then declines in the second stage of diffusion. The result basically follows the behavior of X in figure 6.10: more output yields higher consumer welfare. For high γ, consumer surplus is not as high as when γ is low. Producer surplus increases very sharply in the neighborhood of the corner states for relatively low γ. This effect comes from the high aggregate level of X_d and X_c when s is close to 0 and 1 respectively. Because output and product prices are lower when products are closer substitutes, both consumer and producer surplus are also lower compared to the situation with strongly differentiated products.

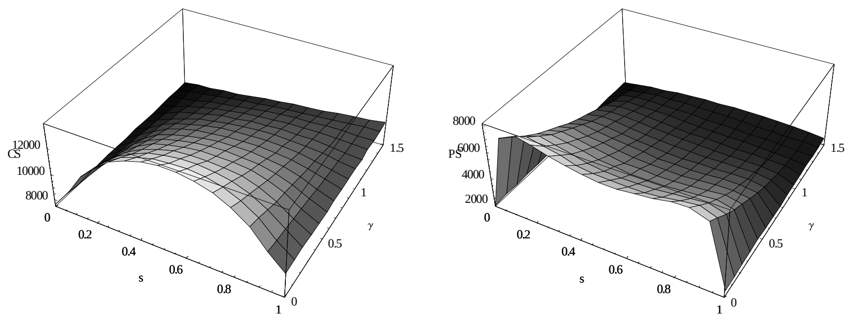

Figure 6.12: *Consumer and producer surplus as function of diffusion and cross-price parameter* γ.

Figure 6.13 shows total welfare as the sum of consumer and producer surplus. The behavior is in line with figure 6.10, which shows the change in industry output X. That is, in general, welfare is lower when the products become closer substitutes (excluding the corner states). Moreover, for low γ welfare first increases in s and then decreases.

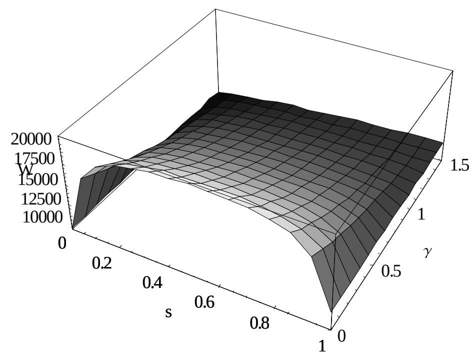

Figure 6.13: *Total welfare as function of diffusion and cross-price parameter* γ.

This finalizes the sensitivity analysis. Before we end this chapter with concluding remarks, we will discuss the stability of the equilibria. The issue is narrowly related to the number of equilibria, given the evolution of the dynamic adjustment process.

6.7 Number of equilibria and stability

In the preceding outline of the model there was a unique interior diffusion equilibrium $\tilde{s}$. Whether or not this applies depends on whether the profit differential is a decreasing or increasing function of diffusion s. This section aims at illustrating these two cases. As stated before, due to compatibility the dynamics is measured by the profit differential $\Delta\pi(s)$. Equation (6.25) shows that for compatible dynamics, $\dot{s} \lesseqgtr 0$ as $\Delta\pi \lesseqgtr 0$. The diffusion state s is a steady state or fixed point if $\Delta\pi(s) = 0$ and an evolutionary equilibrium if it is a local asymptotically stable fixed point. A state s is a Nash equilibrium if no firm benefits from switching technologies at s, i.e., firms are indifferent between applying the two technologies. The number of equilibria depends on the slope of the technology adjustment dynamic (6.26). When $d\Delta\pi/ds < 0$ the unique (interior) Nash equilibrium is at $\tilde{s}$ for which $\Delta\pi(s) = 0$.[9] Alternatively, there are two other equilibria when $d\Delta\pi/ds > 0$; in addition to the interior

[9] See for instance figure 6.2 with a unique interior stable Nash equilibrium in the technology switching game.

Nash equilibria $\tilde{s}$, the corner states $s = 0$ (where $\Delta\pi(s) < 0$) and $s = 1$ (where $\Delta\pi(s) > 0$) are Nash equilibria too. Both the downward and upward sloping case is illustrated and discussed by means of figure 6.14.

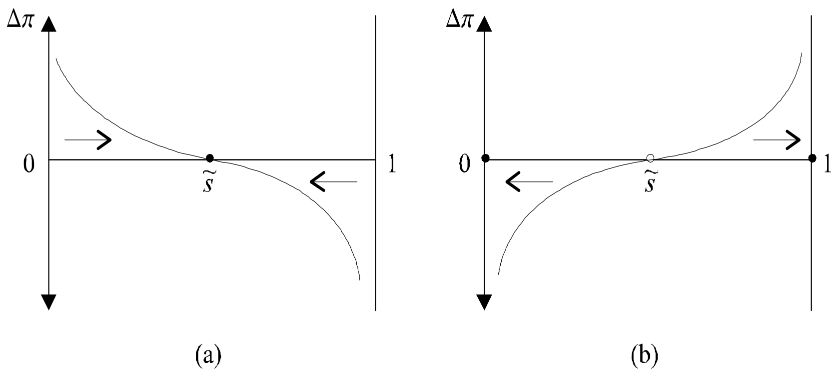

Figure 6.14: *Slope profit differential and equilibria.*

Figure 6.14a shows the downward sloping case as was the case in the numerical example in the previous section. Here $\tilde{s}$ is the only Nash equilibrium. The corner states $s = 0$ and $s = 1$ are no equilibria. In $s = 0$, $\pi_c > \pi_d$ ($\Delta\pi > 0$), inducing dirty firms to adopt the clean technology: s *increases*. On the other hand, a totally clean industry ($s = 1$) is also not an equilibrium. In this state $\pi_c < \pi_d$, inducing clean firms to adopt the dirty technology: s *decreases*. So, for $0 \leq s < \tilde{s}$ diffusion s increases to state $\tilde{s}$ and for $\tilde{s} < s \leq 1$ it decreases towards $\tilde{s}$. More generally, the industry will always end up in the interior Nash equilibrium $\tilde{s}$ from any initial state $s(0)$, making $\tilde{s}$ dynamically stable. It is therefore by definition 3 (see chapter 2) also an evolutionary equilibrium.

Now assume the profit differential is upward sloping as illustrated in figure 6.14b. Following the same line of reasoning, it is now easy to see that $\pi_c < \pi_d$ for $0 < s < \tilde{s}$, hence inducing more firms to become of the dirty type. Ultimately, the whole industry becomes dirty as represented by the state $s = 0$. The reverse happens for $\tilde{s} < s < 1$: then $\pi_c > \pi_d$ and results in a complete specialization in the clean good, i.e., the whole industry becomes clean ($s = 1$). This makes the corner states $s = 0$ and $s = 1$ the evolutionary equilibria. What happens if the industry is in state $\tilde{s}$? By definition, this is a Nash equilibrium, since profits under both technological modes are equal. It is, however, unstable. Even the smallest shock or perturbation makes the industry evolve towards one of the two corner states. In this case, the interior solution $\tilde{s}$ is not an evolutionary equilibrium, but rather a separatrix or threshold that divides the basins of attraction of the evolutionary equilibria $s = 0$ and $s = 1$. Only one firm type exists in these corner equilibria, i.e., either the whole industry is dirty ($s = 0$) or clean ($s = 1$). The corner equilibria mirror a homogeneous technology mode: all firms apply the same technology. Be aware that in this upward sloping case, the comparative statics on the interior solution $\tilde{s}$ have a different interpretation. For example, an increase in $\tilde{s}$ does not mean greater diffusion of the clean technology; if anything it means the opposite, since the shift decreases the chance of ending up at a complete clean industry $s = 1$. However, throughout this thesis we do not consider this case and solely focus on the downward sloping case where the interior solution $\tilde{s}$ is unique and evolutionary stable.

McGinty (2001) provides explicit parameter restrictions for the model discussed in this chapter and finds a unique interior solution if and only if:

$$\frac{\beta}{\gamma} > \frac{\theta_d}{\theta_c}, \frac{\theta_c}{\theta_d}. \tag{6.35}$$

The first term on the right-hand-side of (6.35) should hold in the state $s = 0$. It implies the situation where the profit differential is positive. The reverse case applies in the state $s = 1$. This is reflected by the second term on the right-hand-side of (6.35). Equation (6.35) states that if $\beta/\gamma < \theta_c/\theta_d$ the industry will evolve to the corner state $s = 1$, i.e., all firms will produce the clean good. The opposite occurs when $\beta/\gamma < \theta_d/\theta_c$: there will be complete specialization in the dirty good, i.e., the evolutionary stable state is $s = 0$. Regarding the former case ($\beta/\gamma < \theta_c/\theta_d$), this implies that the profit differential $\Delta\pi > 0$ for all states $s \in [0, 1]$, whereas in the latter case ($\beta/\gamma < \theta_d/\theta_c$) the profit differential $\Delta\pi < 0$ for all these diffusion states s.

Given the demand and cost structure as used in the numerical example of section 6.5, no homogeneous technological mode will become established. The industry will eventually settle in a unique interior state independent of the initial state of the system. Though it might be possible to get the state close to 0 or 1, but it remains the solution $\tilde{s}$ for which $\Delta\pi(s) = 0$ and not $\tilde{s} = 0$ for $\Delta\pi(s) < 0$ and $\tilde{s} = 1$ for $\Delta\pi(s) > 0$. So in case $d\Delta\pi/ds < 0$, diffusion s decreases (increases) whenever $s > (<)\ \tilde{s}$. This makes $\tilde{s}$ also the (unique) evolutionary equilibrium and it is therefore dynamically stable. Note that by compatibility an equilibrium is Nash kind if and only if it is a fixed point and that evolutionary equilibrium implies a Nash equilibrium. Hence an evolutionary equilibrium is a Nash equilibrium refinement (e.g. Friedman, 1998).

Since $\tilde{s}$ is the unique interior long-run Nash equilibrium outcome of the diffusion process, it is also the evolutionary equilibrium (see definition 3 in chapter 2). An evolutionary equilibrium is robust for mutation, i.e., invasion by mutants, noise, trembles etc. We do not explicitly consider a stochastic version of the model which usually includes a 'noise' element. The deterministic model above indirectly takes care of noise and mutation by means of the dynamic stability criterion (e.g. Weibull, 1995). Even the slightest perturbation makes the system come back into $\tilde{s}$. In terms of our economic model it means, for instance, that deviating from supplying the optimal quantity does not affect the system.

At this point we have discussed the underlying adjustment dynamic that drives technology switching and hence the diffusion process and determination of the equilibria. However, in order to find the explicit analytical solution of the interior Nash (evolutionary) equilibrium $\tilde{s}$ for our model, we have to make a modification. Fortunately, this modification does not affect the qualitative behavior of the model as we will see below. Equation (6.17) shows that profits are quadratic in output. Due to this feature the evolutionary equilibrium cannot be derived analytically, even with the existence of a common denominator Θ. However, the solution $\tilde{s}$ can be found by excluding fixed costs, i.e., by assuming fixed costs are zero. Then also analytical comparative statics exercises can be conducted with respect to the evolutionary equilibrium. In order to provide a complete picture, we will now discuss how the model is affected by the assumption of positive fixed costs.

Fixed cost effect

The analysis so far presumed zero fixed costs and the interior Nash equilibrium $\tilde{s}$ (6.29) is the explicit solution to $\pi_d = \pi_c$. By introducing fixed costs $\mu_j > 0$, the profits for both technologies decline by this fixed amount respectively. Since fixed costs are independent of diffusion s, they do not affect the qualitative behavior of the profit functions and hence the profit differential. However, the value of the long-run equilibrium outcome does change. We need to make an adjustment in order to find this equilibrium. Due to the nonlinear relationship between the output quantities and profits, the analytical expression is difficult to find analytically. We therefore only outline the change in direction of the evolutionary equilibrium when positive fixed costs are allowed. Two different situations may happen depending on the slope of the profit differential.

Proposition 1 *When fixed costs* $\mu_j > 0$ *and* $d\Delta\pi/ds < (>) \ 0$, *the interior equilibrium diffusion rate* $\tilde{s}_{\mu_j>0} \gtreqless \left(\lesseqgtr\right) \tilde{s}_{\mu_j=0}$ *iff* $\mu_d \gtreqless \mu_c$.

Proof. In appendix 6A. ■

Proposition 1 simply states that in case of a downward sloping profit differential and with positive fixed costs, the evolutionary equilibrium moves to the left (right) when $\mu_d < (>) \ \mu_c$ relative to the evolutionary equilibrium under zero fixed costs. Under an upward sloping profit differential, the evolutionary equilibrium moves to the right (left) when $\mu_d < (>) \ \mu_c$. Note that the zero fixed cost assumption coincides with the case of positive fixed costs for both technologies being equivalent. The net adjustment effect is then also zero. The fixed cost effect is a constant simply because they enter the profit functions as constants. Given that the profit differential is decreasing in diffusion s, the result of proposition 1 is basically that the lower the fixed costs of the clean technology (μ_c) relative to those of the dirty technology (μ_d), the higher is the equilibrium degree of diffusion. The reverse case holds when the profit differential is increasing in diffusion. Then the equilibrium degree of diffusion becomes lower when μ_c decreases relative to μ_d.

6.8 Concluding remarks

In this chapter we have set up a framework which is suitable for generating and analyzing the diffusion process of an abatement technology in polluting industry of fixed size. Firms play in an imperfect market à la Cournot. Prior to setting optimal quantities, firms choose to produce either by means of a dirty or clean technology. The clean technology differs from the dirty technology in generating lower emissions per unit of output. Technology diffusion is modelled as an evolutionary process on the basis of the short-run profit differential, i.e., the number of firms using the technology with the higher short-run profit level will tend to increase.

The model presented in this chapter shows that the profit differential is decreasing in diffusion, implying the existence a unique interior stable Nash equilibrium. This means that the short-run profit differential, defined as the difference between the profits received under clean production and the profits under dirty production, is positive for relatively low states of diffusion. Hence firms tend to switch from a dirty to a clean production mode. When supplying the clean product, firm-level profits decrease as more firms enter this clean submarket by adopting the clean technology. More generally, the benefits from technology adoption decrease as the number of users increase (*cf.* Karshenas and Stoneman, 1995). The diffusion process halts when the profits under both technological modes are equal to each other and the firms are thus indifferent between them. This is the interior solution, which is the evolutionary stable long-run outcome of the diffusion process and implies that both the clean and dirty type firms coexist in the long-run, i.e., both product variants coexist in the long-run.

The equilibrium degree of diffusion is positively (negatively) related to a positive (ceteris paribus) change in the net absolute advantage of the clean (dirty) firm where the net absolute advantage is defined as the difference between the price intercept and the average variable costs, given the choice of technology. A lower (higher) degree of product differentiation, i.e., a higher (lower) degree of product substitutability, will lead to more (less) number of firms employing the clean technology in the long-run, provided the clean (dirty) firm has a net absolute advantage over the dirty (clean) firm. If neither firm faces a net absolute advantage, the industry comprises in the evolutionary equilibrium 50% of firms producing clean products and 50% of firms producing with the dirty technology.

There is a negative pollution externality resulting from production. Different from what one might intuitively expect, pollution may even increase in the first stage of diffusion of abatement technology. Starting from the initial state of diffusion where all firms produce by means of the dirty technology, an increase of diffusion of clean technology may induce a boost in the aggregate volume of industry production. As the supply of clean products increases, price competition lowers the equilibrium prices, which in turn stimulate demand. The result basically comes down to the effects of technology adoption on the price of the final products as supply increases. The increase in pollution as clean technology starts to crowd out the dirty technology implies that the production effect offsets the positive substitution effect of switching from the dirty to the clean technology. However, the substitution effect will dominate as diffusion of clean technology progresses, hence total emissions decrease and in equilibrium total emissions may be lower than before the introduction of clean technology.

6.9 Appendix 6A

6.9.1 First-order condition

Production x_j either equals zero or meets the first-order condition $\partial\pi_j/\partial x_j = p_j - \beta x_j - \vartheta_j = 0$. Rewriting gives $p_j - \vartheta_j = \beta x_j$. Profits are defined as in (6.10). Suppressing subscript j gives that: $p - \vartheta = \beta x$. Substituting costs (6.7) into (6.10), profits become:

$$\begin{aligned} \pi &= px - c \\ &= (p - \vartheta)x - \mu. \end{aligned}$$

Substituting βx for $p - \vartheta$ returns the profit function as $\pi = \beta x^2 - \mu$. The same procedure can be followed for all other policy regimes (in chapters 7 and 8). The only difference is that the first-order condition now includes additional terms. But following the same routine profits can always be expressed as above.

6.9.2 Proof of proposition 1

Proof. From the first-order condition given above, profits under technology $j = d, c$ can be written as $\pi_j = \beta x_j^2 - \mu_j$. Substitution of this expression into the profit differential $\Delta\pi = \pi_c - \pi_d$ we obtain:

$$\Delta\pi = \beta(x_c^2 - x_d^2) + \mu_d - \mu_c. \tag{6.36a}$$

Let's first consider the situation of a downward sloping profit differential. It is easy to see that in case of $\mu_j = 0$ $(j = d, c,)$ the profit differential is $\Delta\pi = \beta(x_c^2 - x_d^2)$. Because in our model x_j is nonlinear in the state s, the difference in profits $\Delta\pi$ is also a nonlinear function of diffusion s (see figure 6.2). For illustrational purposes and without loss of generality, assume that the profit differential is linear in s. There are two options: either the profit differential is downward or upward sloping in diffusion s. These cases are depicted in figures 6.15a and 6.15b respectively. To explain the fixed cost effect let's focus on the case where $d\Delta\pi/ds < 0$ (figure 6.15a). Explaining the effect for $d\Delta\pi/ds < 0$ (figure 6.15b) is then straightforward.

Assume initially the profit differential $\Delta\pi$ is line A in figure 6.15a. The explicit solution of $\Delta\pi = 0$ generates the long-run equilibrium $\tilde{s}$. Now consider the case where fixed costs $\mu_j > 0$. Then three different cases can occur. First, $\mu_d > \mu_c$. Substituting this into (6.36a) shows that $\Delta\pi$ moves upward simply because a positive constant $\mu_d - \mu_c > 0$ is added. The new situation is line

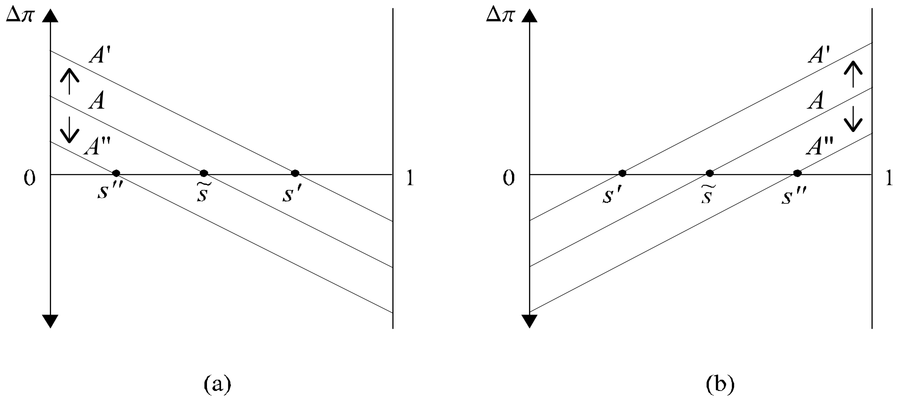

Figure 6.15: *Fixed cost effect and slope profit differential.*

A' with equilibrium $s' > \tilde{s}$. The same routine can be applied to the reverse case where $\mu_d < \mu_c$. The original profit differential A now moves downward with constant $\mu_d - \mu_c < 0$ to line A'' and generates the interior equilibrium s'', which is smaller than the original equilibrium $\tilde{s}$. The final situation that might happen is that the $\mu_d = \mu_c$ In this case the profit differential is equal to the original A because the constant term $\mu_d - \mu_c$ in (6.36a) is zero and hence coincides with the case where fixed costs are zero. ■

6.9.3 Proof equal segregation

Proof. Write $\theta_c = \theta_d = \theta$ and substitute this into the expression for the evolutionary equilibrium under laissez faire (6.29). Then rewriting and rearranging yields that:

$$\tilde{s}^{lf} = \frac{\theta(\beta(N+1) - (\beta + \gamma N))}{2\theta(\beta - \gamma)N} = \frac{\theta N(\beta - \gamma)}{2\theta N(\beta - \gamma)} = \frac{1}{2}.$$

■