Groupe de Recherche en
Économie Théorique et Appliquée

Dynamic efficiency of Extended Producer Responsibility (EPR) instruments in a simulation model of industrial dynamics

Eric BROUILLAT

Vanessa OLTRA

GREThA, CNRS, UMR 5113

Université de Bordeaux

Cahiers du GREThA

n° 2011-14

GRETHA UMR CNRS 5113
Université Montesquieu Bordeaux IV
Avenue Léon Duguit - 33608 PESSAC - FRANCE
Tel : +33 (0)5.56.84.25.75 - Fax : +33 (0)5.56.84.86.47 - www.gretha.fr

Efficacité dynamique des instruments de responsabilité élargie du producteur (REP) dans un modèle de simulation de dynamique industrielle

Résumé

Cet article propose une étude originale de l'impact de la responsabilité élargie du producteur sur les stratégies d'innovation des firmes et les structures de marché. Notre analyse est fondée sur le cadre stylisé de la prévention des déchets élaboré par Brouillat (2009a, b). Les produits y sont modélisés comme des technologies multi-caractéristiques dont l'évolution dépend des stratégies d'innovation des firmes ainsi que des interactions avec les consommateurs et les acteurs de la post-consommation (recyclage). Ce modèle de simulation multi-agents a été ici modifié en vue d'étudier les effets sur la dynamique industrielle des instruments de politique de prévention des déchets, et plus particulièrement leur impact sur les stratégies d'innovation des firmes ainsi que sur l'évolution des caractéristiques des produits et des structures de marché. Nous nous focalisons sur deux types d'instruments réglementaires : la contribution au recyclage et la norme de recyclage. Plusieurs configurations d'un même type d'instrument sont considérées afin d'en étudier les effets sur la dynamique industrielle. La contribution principale de cet article est de montrer comment ce type de modèle de simulation peut être utilisé pour analyser l'impact des instruments de politique de prévention des déchets sur l'évolution technologique des produits, sur les stratégies d'innovation des firmes et sur l'évolution de leurs parts de marché. Introduire une politique environnementale dans un modèle de simulation multi-agents nous permet d'examiner plus en profondeur comment différentes configurations d'un même instrument réglementaire peuvent modifier la dynamique du système et, plus particulièrement, comment les incitations et contraintes liées aux instruments étudiés influencent les mécanismes de sélection à l'œuvre sur le marché.

Mots-clés : Prévention des déchets ; dynamique industrielle ; politique environnementale ; modèle de simulation ; responsabilité élargie du producteur

Dynamic efficiency of Extended Producer Responsibility (EPR) instruments in a simulation model of industrial dynamics

Abstract

This paper presents an original approach to the impact of extended producer responsibility instruments for waste prevention upon firms' innovative strategies and market structure. Our analysis is based on a stylised framework of waste prevention developed in Brouillat (2009a, b). In this framework, products are modelled as multi-characteristic technologies whose evolution depends on firms' innovation strategies and on the interactions with consumers and post-consumption activities (recycling). This model has been adapted to explore the impact of waste prevention instruments upon industrial dynamics, and more particularly upon firms' innovative strategies and upon the evolution of products' characteristics and market structure. We focus on two types of policy instruments: recycling fees and norms. For each instrument, we will consider different policy designs in order to study their effects on industrial dynamics. The main contribution of this paper is to show how this type of simulation model can be used to explore the impact of waste prevention policy instruments on the technological evolution of products, on innovation strategy and on the evolution of firms' market shares. The introduction of policy instruments in a simulation agent-based model of industrial dynamics enables us to analyse more thoroughly how different policy designs can modify the dynamics of the system and, more particularly, how the incentives and the constraints linked to the policy instruments under consideration shape market selection.

Keywords: waste prevention; industrial dynamics; environmental policy; simulation model; extended producer responsibility

JEL: O33, D21, Q53

Reference to this paper:, BROUILLAT Eric, OLTRA Vanessa, 2011, "Dynamic efficiency of Extended Producer Responsibility (EPR) instruments in a simulation model of industrial dynamics", *Cahiers du GREThA*, n°2011-14, http://ideas.repec.org/p/grt/wpegrt/2011-14.html.

1. Introduction

This paper presents an original approach to the impact of environmental policy instruments for waste prevention upon firms' innovative strategies and market structure. Today waste prevention and reduction is a core aspect of extended producer responsibility (EPR). The basic principle of EPR is to place some responsibility for environmental impact of product's end-of-life on the original producer and seller of that product. The thinking behind this approach is that it will provide incentives for producers to make design changes to products that would reduce waste management costs (OECD, 2006). The literature on EPR generally assumes that any form of EPR will provide incentives to firms to change their products and practices towards eco-design, but there is little conceptual thinking on how such incentives work through the system (OECD, 2006). Models on EPR instruments generally assume that producers choose material inputs and the level of output to maximize profits and that consumers choose how much to consume, recycle and throw away so as to maximize utility subject to budget constraints. A majority of models assume perfect competition on the output market, and do not endogenize recycling activities nor R&D activities and innovation in eco-design[1]. Within this literature, the focus is on the impact of EPR instruments on social welfare and so on the role of economic instruments and prices in order to provide optimal incentives to firms and to consumers for reducing the environmental effects of post-consumer products to the optimal level (see for example, Palmer and Walls (1997); Fullerton and Wu (1998); Calcott and Walls (2005)). Yet the main objective of EPR is to promote innovation and to stimulate producers to design products that are more environmentally compatible (i.e. design for the environment). As pointed out by Kneese and Schulze (1975), besides the issue of static efficiency, the extent to which policy instruments spur new technology 'toward the efficient conservation of environment' is one of the most important criteria on which to evaluate the efficiency of environmental policy instruments. This argument is particularly true in the case of EPR instruments. But in order to be able to discuss the dynamic efficiency of EPR policy instruments, one need to take into account learning mechanisms, as well as uncertainty and path-dependency phenomena characterizing innovation activities (Dosi, 1988). In other words, an analysis of the impact of EPR instruments on firms' capacity to innovate implies to endogenize firms' R&D and eco-design activities. This is the main purpose of this article which explores the dynamic efficiency of two different EPR policy instruments i.e. recycling fees and norms, in an agent based simulation model in which technological progress is driven by an endogenous stochastic innovation process relying on firms' R&D strategy.

The model is based on a stylised framework of waste prevention developed in Brouillat (2009a, b). In this framework, products are modelled as multi-characteristic technologies whose evolution depends on firms' innovation strategies and on the interactions with consumers and post-consumption activities (recycling). Brouillat (2009a, b) develops a micro-simulation model enabling to study the dynamics of waste prevention and the development of green products through dynamic stochastic processes involving multiple compromises and trade-offs between the different dimensions of products i.e. technological performances, recyclability and competitiveness. The main contributions of this model are to introduce recyclability as a characteristic of products, to study the interactions with the other characteristics and to integrate endogenous recycling activities and raw materials flows.

[1] For a survey, see Walls (2004) and OECD (2006).

In this paper, we use the same model in order to explore the impact of waste prevention instruments upon industrial dynamics, and more particularly upon firms' innovative strategies and upon the evolution of products' characteristics and market structure. The main contribution of the paper is to model EPR policy instruments in a complex adaptive system composed of three types of interacting agents i.e. producers, consumers and recyclers, and whose evolution is based on a stochastic and path-dependent innovation process. The introduction of policy instruments in such simulation agent-based models of industrial dynamics enables us to analyse more thoroughly how different instruments and designs can modify the dynamics of the system and, more particularly, how the incentives and the constraints linked to the considered policy instruments shape market selection and innovation. Moreover, this is done in a bounded rationality context *à la Simon* in which agents facing uncertainty are not able to optimize expected profits. Our purpose is to test in such context the relative dynamic efficiency of recycling fees and norms.

The paper is organized as follows. In section 2 we present the model. In section 3 we present some simulation results and we compare the effects of different policy instrument settings on innovation and selection. In section 4 we draw some final conclusions.

2. Recycling fees and norms in a model of industrial dynamics

2.1. Basic structure of the model

Before describing the model, a warning note is required. Our goal is to build a model that can provide us with generic lessons about the impact of EPR policy instruments on the development of eco-products. The purpose is to shed light on the conditions and the mechanisms driving change in firms' innovation strategy and the associated shift to green or eco-products. Our results must be considered as indicative rather than as predictive. Real world markets are so complex that, even if we were able to build a good approximation of one of them, we would face the same problems of generalization than with real data.

The structure of the model is based on “history-friendly modelling" developed by Malerba et al. (1999, 2007, 2008). We use the same kind of topography to characterize products and the way of modelling innovation and market dynamics is very similar. However, our model is not a history-friendly model, in the sense that we do not aim at generating stylized facts to reproduce the dynamic of a given industry. Our approach is rather counterfactual in the sense that we aim at exploring the properties of a virtual industrial system, which is modelled as a complex adaptive system, under different condition settings.

The model is based on a previous work on firms’ economic incentives to extend product lifetime and recyclability of products (Brouillat, 2009a, b). However, this model has been adapted in order to address the policy question under examination. In this section, we will highlight these modifications. Given the complexity of agent-based models, it is impossible to present in details all the equations without confusing the reader and obscuring the basic logic of the model. We will therefore describe in transparent form what we regard as the central ideas of the simulation model[2].

We consider the market of a generic durable product. We take into account three categories of actors: firms producing and marketing a single finished product (i)[3], end

[2] Interested readers may obtain a full copy of the simulation model by writing to the authors.
[3] Consequently, *i* represents the product as well as the producer.

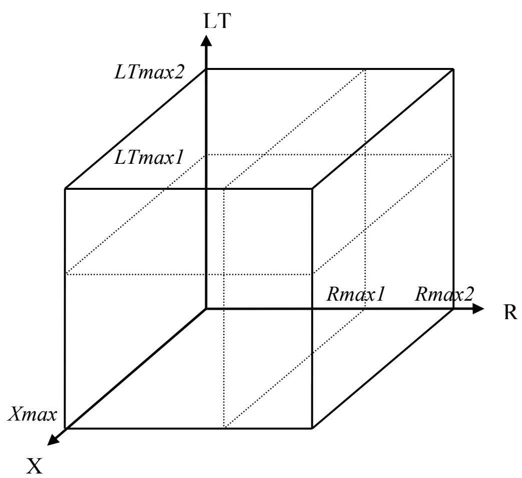
consumers buying those products, and recyclers recovering and recycling end-of-life products used by consumers. These three categories of agents interact at the various stages of the model. There is no entry of new agent in the model.

- Product space

An important aspect of the model is the topography of the products' space. Every product is modelled in a Lancasterian way that is as a vector of three characteristics which determine its quality level. These three characteristics are recyclability (*R*), durability (*LT*) and technical quality (*X*). *X* reflects the "conventional" quality of products. It is a multi-criterion dimension reflecting the performance of the technical attributes during the use phase. *X* is a synthetic index which increases in proportion to the overall technical quality of the product.

For each characteristic, we assume outer limits which delimit the achievable potential with the existing design of products. It was presumed that there is a maximum recyclability threshold (*Rmax1),* a lifetime threshold (*LTmax1)* as well as a maximum technical quality (*Xmax*) defining the technological frontier on each dimension. For analytic convenience, we treat those technological constraints as defining rectangular boxes in a three dimensions space (cf. figure 1). Thus the 'boxes' in figure 1 depict the set of technological characteristics that can potentially be achieved in product design. This means that firms' innovative activities will be carried out within this product space.

Figure 1. Product's quality attributes



The distinction between incremental and radical innovation is important to discuss the dynamic efficiency of EPR policy instruments. EPR approaches could lead to no innovation, incremental innovation or radical innovation. Both types of innovation may decrease energy and materials consumption and increase the recyclability of products. Even if it is difficult to distinguish between what constitutes incremental and radical innovation, we propose to define incremental innovations as innovations bringing improvements in product characteristics within the boundaries of the existing product design space (*Rmax1* and *LTmax1*), whereas radical innovations enable firms to exceed the thresholds by radically modifying the design of their products. This is consistent with the definition given by Stevens (2004) according to which "radical innovation would be in the holistic approach of design for the environment". Green product design includes designing products in their entirety that can be easily upgraded, rather than replaced, or that can be easily disassembled for reuse or recycling (Stevens, 2004). Based on the topography of our product space, it means that (*Rmax1)* and

(*LTmax1*) represent the maximum recyclability and lifetime reachable through incremental innovations, while radical innovations enable firms to exceed those thresholds. In other words, a radical innovation in the design of product opens new technological opportunities and push technological boundaries up to (*Rmax2*) and to (*LTmax2*). So in terms of environmental performances, radical innovations in product design open a new potential of improvement in the recyclability and lifetime of products, which can be conducive (if efficiently exploited by firms) in the long run to a significant decrease in waste streams and virgin material flows.

- Innovation process and R&D strategy

Figure 1 represents the product space in which each firm will progress (thanks to its innovative activities) along a specific technological trajectory. Every firm tries to improve the quality of its product on one or several dimensions in order to make it more attractive towards consumers. These improvements and the direction of firm's trajectory will depend on its R&D strategy.

The model integrates an endogenous process of knowledge accumulation and innovation. At each period, every firm invests in R&D a fixed proportion of its profits of the previous period. The R&D investment seeks to improve the quality of products. Such a rise in product quality will give the firm an opportunity to increase its market share. R&D investment (*RD*) is divided into expenditure aiming at increasing the product technical quality (RD^X), the lifetime (RD^{LT}) and the recyclability (RD^R):

$$\mathrm{RD}^{X}_{i,t} = \delta^{X}_{i,t}.\mathrm{RD}_{i,t} \qquad (1.a)$$

$$\mathrm{RD}^{LT}_{i,t} = \delta^{LT}_{i,t}.\mathrm{RD}_{i,t} \qquad (1.b)$$

$$\mathrm{RD}^{R}_{i,t} = \delta^{R}_{i,t}.\mathrm{RD}_{i,t} \qquad (1.c)$$

The firm specific variables δ^X, δ^{LT} and δ^R reflect the firm's distribution of R&D expenditure and, consequently, its innovation strategy regarding product's characteristics ($\delta^X+\delta^{LT}+\delta^R = 1$).

The successive R&D investments allow accumulating knowledge (*S*) about each of the three quality dimensions:

$$S^{X}_{i,t} = \eta.RD^{X}_{i,t} + (1-\eta).S^{X}_{i,t-1} \qquad (2.a)$$

$$S^{LT}_{i,t} = \eta.RD^{LT}_{i,t} + (1-\eta).S^{LT}_{i,t-1} \qquad (2.b)$$

$$S^{R}_{i,t} = \eta.RD^{R}_{i,t} + (1-\eta).S^{R}_{i,t-1} \qquad (2.c)$$

with the parameter η ($0 \leq \eta \leq 1$) determining the speed at which the level of knowledge fits the R&D expenditure of the current period.

This accumulated knowledge will be used to innovate: for each firm, the level of knowledge determines the probabilities of access to new values within product space. Access probabilities to a new technical performance are logistic functions of the knowledge level reached in terms of technical quality (S^X). The same applies to both dimensions *LT* and *R* using the knowledge level reached in terms of product lifetime (S^{LT}) and recyclability (S^R).
The innovation process involves increasing the value of at least one of the three product's characteristics according to Cobb Douglas functions. For example, the improvement of the technical quality is given by:

$$\Delta X_{i,t} = \alpha_X . \left(S^X_{i,t}\right)^{\gamma_1} . \left(Xmax - X_{i,t-1}\right)^{\gamma_2} . \left(E_{i,t}\right)^{\gamma_3} \qquad (3)$$

This equation implies that the increase in technical quality depends on the knowledge level reached in this dimension (S^X), the distance of the achieved design to the frontier (*Xmax* – *X*) and the cumulated experience (*E*) (i.e. the number of periods that the firm has been working with a particular product design). The same applies to product lifetime and recyclability[4]. The effect of the distance to the frontier implies that when the level of a given product characteristic comes closer and closer to the limit of what is achievable with the considered product design, a given R&D expenditure will achieve less and less further progress (traditional effect of depletion of technological opportunities).

In the present model, firms' R&D strategies may change over time in order to fit their behaviour to the fluctuations of the market environment[5]. Firms' innovative strategies are then characterized by a learning process in the form of two operators, imitation and mutation (Silverberg and Verspagen, 1995). The learning process is divided into two steps. The first step determines if the firm wants to change its R&D strategy, while the second fixes the new strategy. This learning is based on a Simonian approach of bounded rationality so that firms take their decisions according to satisficing rules: only the firms with unsatisfactory profit levels will choose to change their strategy. Firms will decide then to change their R&D strategy with probabilities proportional to their gross profits (*Π*) and the best and the worst profits observed on the market in the current period (*Πmax* and *Πmin*):

$$\mathrm{Prob}^{\mathrm{Change}}_{i,t} = k.\left(1 - \frac{\Pi_{i,t} - \Pi\min_t}{\Pi\max_t - \Pi\min_t}\right) \qquad (4)$$

Parameter *k* is the maximal probability. Thus, the more profitable a firm is, the less likely it will change its strategy. If the draw is a success, the firm will review its R&D strategy; if not, the firm retains its strategy from the previous period.

Once the firm has decided to change its strategy, two possibilities arise:

- The first one consists in imitating the strategy of a competitor. The firm randomly selects a firm in the economy with probabilities proportional to firms' market share. Once the firm has chosen the competitor to imitate, it adopts the strategy of this firm by imitating the value of the variables δ^X, δ^{LT} and δ^R.
- The second possibility consists in selecting a new strategy without taking into account the behaviour of the other firms (mutation). The firm will draw from a normal distribution and alter the value of its variables δ^X, δ^{LT} and δ^R within the admissible range [0,1][6].

As explained in the description of the product space, when a firm crosses the boundaries *Rmax1* and/or *LTmax1,* it implies a change in the product design which corresponds to what we call a radical innovation. We assume that such change in product design requires a transition period over which the firm will face additional fixed costs (a kind of switching cost). These costs will be borne by firms over several periods following radical innovation and consequently, it will lower profits[7]. Net profits are then equal to gross profits minus the fixed costs due to the change in product design. These net profits play the role of financial constraint by determining the budget allocated to R&D.

[4] This formulation is inspired from Malerba and al. (1999, 2007).
[5] The evolution of R&D strategy is a new aspect of the model comparatively to Brouillat (2009a, b).
[6] The firm will randomly choose between imitation and mutation with probabilities proportional to its imitation propensity. We assume that imitation propensity is a parameter identical for all the firms.
[7] Additional costs and the duration of payment are identical for all the firms.

Moreover radical innovation entails another effect that we call 'experience destroying effect' linked to the decrease to zero in the experience variable (*E*) (cf. equation 3). This effect is due to the fact that a radical innovation involves a complete change in the product design (design for environment), so that the experience developed with the old product design counts for little or nothing when the firm shifts to the new eco-design. But in the meantime, radical innovation opens new technological opportunities to firms since it pushes the boundaries to *Rmax2* and *LTmax2,* so that the distance to the technological frontier increases which will pull up the potential improvements in product quality. To summarize, radical innovations benefit to firms in terms of dynamic efficiency in the long run (i.e. it opens new technological opportunities), while in the short run they entail constraining effects for firms in terms of fixed costs and experience.

- Demand side

The demand for products is expressed as a demand for specific product characteristics in a Lancasterian vein. A simple formulation of consumer preferences is based on the following visibility function. We assume that each consumer uses one single product at the same time and renews its purchase only when this product is at the end of its lifetime or when it becomes obsolete. The rule to choose a new product is random, with probabilities proportional to what we call products' visibility (*V*)[8]:

$$V_{i,t} = \left(X_{i,t}\right)^{\beta_1} . \left(\frac{\widetilde{L}T_{i,t}}{p_{i,t}}\right)^{\beta_2} . \left(\widetilde{R}_{i,t}\right)^{\beta_3} . \left(MS_{i,t-1}\right)^{\beta_4} \qquad (5)$$

The visibility of the product is a specification of its total performance, i.e. in terms of its characteristics and market share. This function implies that visibility increases with the quality of the product and decreases with its selling price (*p*). Furthermore, the relative increase in visibility is a weighted average of the relative increases in each attribute. Parameters β_1, β_2 and β_3 represent sensitivity of the visibility respectively to technical quality, product use cost (*LT/p*: price per period of use) and recyclability. *MS* is the market share of the firm and the parameter β_4 reflects the bandwagon effect (Lebeinstein, 1976). The parameters β_1, β_2, β_3 and β_4 represent, then, the consumer's preferences with respect to the product's characteristics[9]. Malerba et al. (2007) suppose that a certain section of consumers have a strong preference for one product characteristic ("experimental users"). In the same way, we assume that a certain section of consumers called "green consumers" have a strong preference for environmental characteristics of products. In fact, in developed countries, an increasing attention towards environmental issues can be observed, making responsible consumption a critical choice for many individuals, but not by all. Green consumers pay greater attention to product recyclability ($\beta_1 < \beta_3$) while non-green consumers are more interested in its technical performance ($\beta_1 > \beta_3$).

We assume that consumers cannot perfectly know the environmental quality of products and cannot estimate perfectly reliability of products. Consequently, we assume that consumers' decisions are based upon their own perceptions of the recyclability and lifetime of products ($\widetilde{L}T$ and $\widetilde{R}$) and that these perceptions result from random draws in a normal distribution centred on the actual values.

As to the replacement of products, we assume that consumers can renew their product (before its end of life) when it is still in working order because the technical characteristics of

[8] This function is based on the utility function of Malerba et al. (1999).

[9] We assume that $\beta_1 + \beta_2 + \beta_3 + \beta_4 = 1$

this product do not satisfy their expectations anymore. The modelling of these renewal decisions is based on obsolescence probabilities depending on the technical quality (*X)* of the products currently used by consumers in the current period. The higher the technical quality of the product, the less likely it will be considered as obsolete. Thus, consumer *j* will replace its product before its end of life according to the following obsolescence probability ($prob^{Obs}$):

$$\text{prob}_{j,t}^{\text{Obs}} = x_j . \left(1 - \frac{X_{j,t} - \text{MinX}_t}{\text{MaxX}_t - \text{MinX}_t}\right) \qquad (6)$$

X_j is the technical quality of the product owned by consumer *j*, *MinX* and *MaxX* are the best and the worst technical quality (*X)* of the products currently used by consumers on the market in the current period and *x* is a parameter reflecting the maximum obsolescence probability[10].

At the end of the purchase cycle, each firm counts the number of sales (*Q*) and the number of lost users (*LOST*) and consequently determines the current number of users of that product, i.e. its stock of customers (*U*):

$$U_{i,t} = U_{i,t-1} + Q_{i,t} - LOST_{i,t} \qquad (7)$$

The market share of the firm (*S*) is given by this stock of customers:

$$S_{i,t} = \frac{U_{i,t}}{\sum_{i=1}^{n} U_{i,t}} \qquad (8)$$

Regarding the exit process, we assume that firms will decide to leave the market if they cannot face their production costs over a too large number of consecutive periods. In our simulations, we consider that firms will exit the market if they make losses (negative net profits) over a least ten consecutive periods.

- Firms-recycler interactions

We assume that manufacturing products requires two categories of substitutable inputs: recycled inputs and virgin inputs[11]. Thus, to produce the quantity *Q*, the firm *i* needs a quantity $\omega_i.Q$ of recycled inputs and a quantity $(1 - \omega_i).Q$ of virgin inputs. Parameter ω_i represents the share of recycled inputs constituting the product ($0 \leq \omega_i \leq 1$). Recycled inputs are provided by recyclers, virgin inputs by suppliers external to the model.

The recycler is the main actor within the post-consumption phase. To simplify, we are assuming that there is just one single recycler in the economy. This agent will represent all the downstream actors in the supply chain. She collects the complete range of end of life products which she recycles, depending on the recyclability (*R*) of these products[12], and sells to the firms as recycled inputs[13]. Recycled inputs are then available in limited quantities. We note, respectively *qr* and *qv* the quantities of recycled and virgin inputs bought by the firm from the recycler and virgin inputs suppliers to manufacture the quantity *Q*. If the recycler provides a sufficient quantity of recycled inputs to face the demand, each firm buys the desired quantity of recycled inputs ($qr = \omega.Q$). But, if the available quantities of recycled inputs are not

[10] Consumers owning a product with the highest performance will have an obsolescence probability equal to zero, those owning a product with the lowest performance will have the maximum probability *x*.
[11] We are actually supposing that virgin inputs can be used as substitutes for recycled inputs.
[12] Starting from a unit of end of life product, the recycler manufactures and sells *R* units of recycled inputs.
[13] We are assuming that the part which cannot be recycled is incinerated or stocked in a waste disposal site.

sufficient to feed the demand, firms will buy in an additional quantity of virgin materials to face the recycled inputs shortage[14]. *qr* and *qv* enter in the calculation of product price.
The price of a product is defined as the product unit cost of production from the previous period (*CM*) to which the firm adds a fixed mark-up (λ):

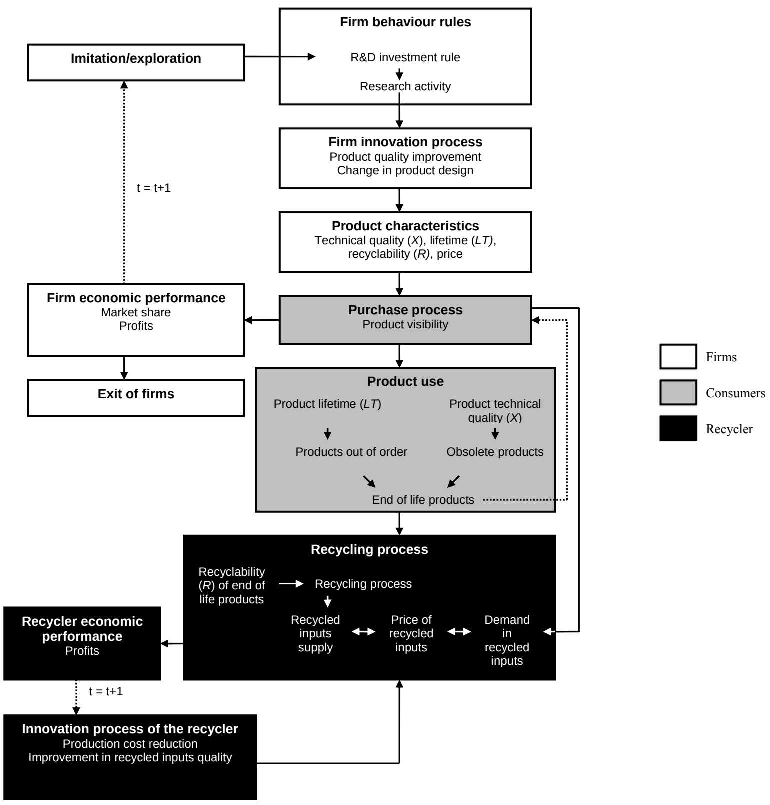
$$p_{i,t} = (1+\lambda).CM_{i,t-1} = (1+\lambda).\frac{(pr.qr_{i,t-1} + pv.qv_{i,t-1})}{Q_{i,t-1}} \quad (9)$$

λ is identical for all the firms so that there is no price strategy in the model. Firms compete on product innovation and their strategy only focus on the distribution choice of R&D expenditure. *pr* is the price of recycled inputs and *pv* the price of virgin inputs. *pv* is exogenic, fixed by virgin inputs suppliers. By simplification, we assume that *pr* is also fixed[15].

At each period, the recycler invests in R&D a fixed proportion of its profits of the previous period in order to increase the quality of its recycled materials and to lower its marginal production cost[16]. The modelling of R&D investment and innovation process of the recycler is based on the same principles than the one of firms.

Improvements in recycled materials quality will increase the demand for this type of inputs, i.e. the share of recycled inputs constituting products (ω) will increase for all the firms on the market. Improvements in production efficiency of the recycling process will lead to lower the marginal production cost of the recycler and then will contribute to increase its profits. Figure 2 summarizes the model structure and the interactions among agents.

Figure 2. Model structure



[14] Consequently, we assume that there is no constraint in the quantity of virgin inputs.
[15] There is no fixed condition on the value for *pv* and *pr*. *pv* can be higher, lower or identical to *pr*.
[16] We have to notice that the production cost of the recycler is characterized by large fixed costs because recycling activities requires a large capital stock (machines, infrastructure, etc.).

2.2. Modelling recycling fees and norms

The main contribution of this model is to simulate the impact of two EPR policy instruments in a model in which the dynamics is mainly driven by an endogenous stochastic process of innovation.

We assume that public authorities set a regulatory framework aiming to turn market dynamics towards better environmental performance, i.e. lowering quantities of waste and increasing recycling rates. Nevertheless, the decision-making process guiding the implementation of regulation is not endogenous to the model. We only consider the introduction of policy instruments, which are exogenously designed, and study their effects upon the dynamics of the simulated system. We assume that public authorities are fully informed about the performance level of firms and so are able to control and to monitor them to ensure that regulation is fully respected.

EPR encompasses a range of instruments which will be analysed in terms of their innovative effects. As usual in environmental policy analysis, two main types of instruments can be distinguished: regulatory instruments (take-back requirements, recyclability norms and product standards) and economic instruments (deposit/refund schemes, advance disposal or recycling fees, material taxes, pollution charges and subsidies). Take-back requirements are the primary EPR instrument. They require producers or retailers to take back the product or its packaging after use. They are often associated with targets for collection and recycling and have been applied to a wide range of products (OECD, 2006). Take-back mandates are often associated to other instruments, in particular advance disposal or recycling fees and recycling norms. These two instruments are introduced in the model.

- Recycling fees

In order to cope with take-back and recycling responsibility, producers have two options: either they develop internally some processes for the disposal and the recycling of end of life products, either they sub-contract these activities to eco-organizations or to recycling firms. Generally, firms prefer this last solution since the internal development of recycling systems involves high financial and organizational investments (Mayers, 2007). Thus in most cases, take-back mandates take the form of "advanced recycling fees" which are paid by firms to recycling organizations. A recycling fee is generally a tax assessed on product sales and used to cover the cost of recycling. The calculation and the distribution of recycling fees can follow different principles[17]. The main issue is to determine who is going to pay the tax: producers or consumers? If producers are required to pay the fees, they may have the incentive to try to reduce the fees instead of redesigning their products (Stevens, 2004). If consumers pay, it may have a significant impact on price but not on product innovation. Another important point concerns the reward effect linked to recycling fees. In OECD (2006), Walls emphasizes that it is essential that the reward is linked to efforts on part of individual producer not to industry-wide effect.

In order to take into account these different effects, we consider different designs of recycling fees. We assume that for each sale, firms are required to pay the recycler for the recycling of their products. As to the calculation of the recycling fee, we study two cases. In the first case, we model a single fee homogeneous for all the firms: the fee is proportional to the average recyclability of products on the market. In that case, the fee depends on the industry wide effort on recyclability:

[17] For a survey on these policy instruments, see for example OECD (2006).

$$Fee_t = FeeRate \cdot \left(\frac{R\max 2}{\overline{R}_t} \right) \qquad (10.a)$$

$$\text{with } \overline{R}_t = \frac{\sum_{i=1}^{n} R_{i,t} \cdot Q_{i,t}}{\sum_{i=1}^{n} Q_{i,t}}$$

In the second case, the fee is specific to firms, i.e. proportional to the recyclability of the products sold by each firm:

$$Fee_{i,t} = FeeRate \cdot \left(\frac{R\max 2}{R_{i,t}} \right) \qquad (10.b)$$

The parameter *FeeRate* is the minimum value for the recycling fee. The fee is in the meantime an extra cost for firms and an additional financial resource for the recycler. As already mentioned, this cost can also be supported by consumers. Indeed in order to prevent a drop in firms' profits, authorities could permit firms to integrate the fee into their product price (Clift and France, 2006). In this case, consumers will pay for the recycling of their product.

So, we consider four types of design for this instrument:

- Homogeneous recycling fees paid by consumers (HC).
- Homogeneous recycling fees paid by firms (HF).
- Firm specific recycling fees paid by consumers (SC).
- Firm specific recycling fees paid by firms (SF).

- Recycling norms

Product take-back mandates are often associated to recycling rate targets. For example, the government may require that each producer meets a recycling rate goal of, says, 75%. In Europe, many packaging laws work in this way and material-specific recycling rate targets or norms are set (OECD, 2006). These instruments can stimulate product innovations as well as increased recycling and reuse of products. But as emphasized notably by Ashford (2000, 2002), the impact of every policy instruments depends on its design and in particular on its stringency. In the case of recyclability norms, stringency depends on the level of the norm as well as on the mechanisms of control and penalties in case of non-compliance.

Concerning the calculation of the level of the recyclability norm (*Rmin*), we assume that it is set by applying a parameter *NormRate* to the highest product recyclability on the market (*MaxR*) when the norm is introduced. It means that we assume that the norm is fixed according to the best technology in terms of recyclability available on the market:

$$R\min = NormRate \cdot MaxR_{t=START} \quad (11)$$

with $0 < NormRate \leq 1$.

Then we consider two policy designs characterized by different stringency levels:

– The most stringent norms (Norm1) require that all products on the market provide an environmental performance at least equal to that required by the norm. After the introduction of the norm, only the products which comply with this requirement will be considered suitable for sale. The products providing a recyclability level lower than

Rmin will not be allowed to be marketed (case Norm1). In that case, the norm really plays as a selection mechanism.

– We will also study a less stringent regulation (Norm2): firms not satisfying the norm will be asked to pay a fine, as the environmental performance of their product is below this standard. The calculation of the fine is based on the average firm profits:

$$\text{Fine} = \text{FineRate} \,.\overline{\Pi}_{t=\text{START}} \quad (12)$$

with $\overline{\Pi}_t = \frac{\sum_{i=1}^{n} \Pi_{i,t}}{n}$

FineRate is a parameter reflecting the stringency of the fine ($0 < FineRate \leq 1$).

By varying the characteristics of norms, we can consider different policy designs, in particular in terms of stringency, and study how it affects industrial dynamics. Both policy instruments with their different designs are evaluated on the basis of the simulation results presented in section 3.

2.3. Objectives and dynamic efficiency of policy instruments

The first step in designing and implementing an efficient policy is clarifying the environmental objective of the policy. The problem with EPR instruments is that they are supposed to achieve several objectives: waste diversion, reduced environmental impact from production, less use of virgin materials in production and reduced toxicity of products. However one policy instrument cannot achieve all of these goals. As emphasized by Walls (2004), the primary objective if EPR policy should be to reduce the volume of solid waste disposal, while promoting recycling is seen as a mean of cost-effectively reducing waste disposal. “Likewise, encouraging producers to design for environment is a means to an end and not an end itself”, (Walls, 2004, page 28).

In our model, the environmental objectives of EPR instruments are fixed according to this scheme, by considering that the priority is to decrease the volume of non-recycled waste as well as the use of virgin materials. Consequently, the environmental objectives of EPR instruments are primarily linked to two variables, which are the quantity of virgin materials flows used in the industry and what we call the “recycling rate” of waste which is calculated as the amount of recycled waste over total waste streams. Virgin materials flows are expected to decrease while recycling rate is expected to increase when an EPR policy instrument is introduced.

The literature of environmental policy instruments tends to show that economic instruments are more advantageous than regulatory instruments in terms of (static) cost efficiency. But as outlined by Requate (2005), the extent to which policy instruments spur both R&D and the adoption of environmentally-friendly technology is one of the most important criteria on which to judge the performance of policy instruments. This capacity to stimulate a dynamic process of knowledge development and innovation is what is called the dynamic efficiency of instruments. In the case of EPR instruments, dynamic efficiency mainly concerns the capacity of the instrument to encourage producers to innovate and to design their product for environment. In our model, the dynamic efficiency of policy instruments can be evaluated through the change in firms' R&D strategy (share of R&D invested in recyclability), as well as through their capacity to innovate and to increase the recyclability of their products and to change their product design (radical innovation). To summarize, we can say that in our model the dynamic efficiency of policy instruments is related to the capacity of each instrument to provide incentives to firms to change their products towards eco-design and to progress in the long run in the product space.

The question of dynamic efficiency is often discussed in relation to the Schumpeterian trade-off between innovation and monopoly power. The literature shows that in strongly cumulative markets, there is a strong tendency towards concentration and some sort of 'natural monopoly' linked to innovation. This tendency can be overcome by antitrust policy, but this "may create a new policy problem since a reduction in market power […] might be associated with a reduction in the rate of technical change because the size of leading firm is greatly reduced and investments in R&D are lower; consequently technological advance is reduced" (Malerba et al., 2008, page 375). In our model, the Schumpeterian trade-off is quite active since market dynamics is highly cumulative: the innovation process is path-dependent and cumulative (cf. equation 3), and market demand includes a bandwagon effect (cf. equation 5) which reinforces cumulativeness. Even if the question of market competition is not crucial in our article, the impact of EPR instruments must also be evaluated in terms of market efficiency i.e. their effects upon concentration. Through simulation, we will explore how the introduction of some EPR policy instruments may affect market dynamics and so the tendency towards concentration. As a matter of fact, policy instruments can influence the selection environment and so the evolution of firms' market shares (which in turn shapes their capacity to innovate). For that reason, EPR policy instruments will also be evaluated in terms of their market efficiency by considering their effects upon concentration, price as well as upon firms' profits and exit rate.

In summary, EPR instruments will be evaluated and compared according to three types of criteria: environmental efficiency, dynamic efficiency and market efficiency (summarized in table 1).

Table 1. Efficiency criteria and objectives of EPR instruments

Efficiency criteria	Objectives
Environmental efficiency	- To decrease the total quantity of virgin materials used - To increase in the share of recycled waste
Dynamic efficiency	- To provide incentives to R&D on recyclability - To increase product recyclability - To stimulate changes in product design (radical innovation)
Market efficiency	- To control the impact of EPR instruments on market concentration, price, firms' profits and failure rate

3. Dynamic efficiency of EPR policy instruments: simulation results

As emphasized by many authors, in particular Ashford (2000, 2002), the effects of policy instruments upon innovation depend more on the policy design than on the type of instruments. That is to say that a given policy instrument may have different effects according to the way it is implemented, and more particularly according to its stringency *versus* flexibility and its time frame. It is within this perspective that we consider different rules or designs for each instrument.

Two types of complementary results will be sequentially presented and examined in this section. First, we will study the dynamics of the system using one single simulation run. This simulation exercise is useful to explore and to understand the phenomena unfolding during the virtual history of a simulation run. It will enable us to investigate step by step firms' trajectories as a result of the interplay of market dynamics and technological change. It will also cast light on the impact of regulation on these trajectories, on market structure and aggregated environmental variables.

In a second step, we will explore the properties of the model with a wide range of parameter settings. The purpose is to see if we can identify some emergent properties and results which can be considered as valid for the whole set of parameters. To this end, we will present the results coming from a battery of 10000 simulations carried out with a Monte Carlo procedure. This methodology enables us to run a high number of simulations with a random setting of the initial values of the parameters of the model (Table 1 in appendix presents the chosen domain for the most important parameters). It is a way of exploring the space of parameters and of emphasizing the variety of the possible outcomes of the model without an arbitrary initialization of the parameters. In particular, it will enable us to test the effects of regulation parameters on the model dynamics and to hold out general proposition about the impact of policy instruments on the market. This will be done in the last section through regression trees which emphasizes the most influential parameters of EPR policy designs.

3.1. Exploring one simulation run: firms' trajectories and effects of policy instruments

In this simulation experiment, we formalized initially 8 firms, 1000 consumers and one recycler. Table 2 in appendix presents the chosen values for the main parameters. We run 7 simulations (corresponding to the six considered policy designs plus the case without regulation) that we will compare regarding different variables[18]. We run the first simulation without any regulation, and then one run for each policy instrument (Norm1, Norm2, HC, HF, SC and SF). Figure 3 and 4 presents the results of the simulation run.

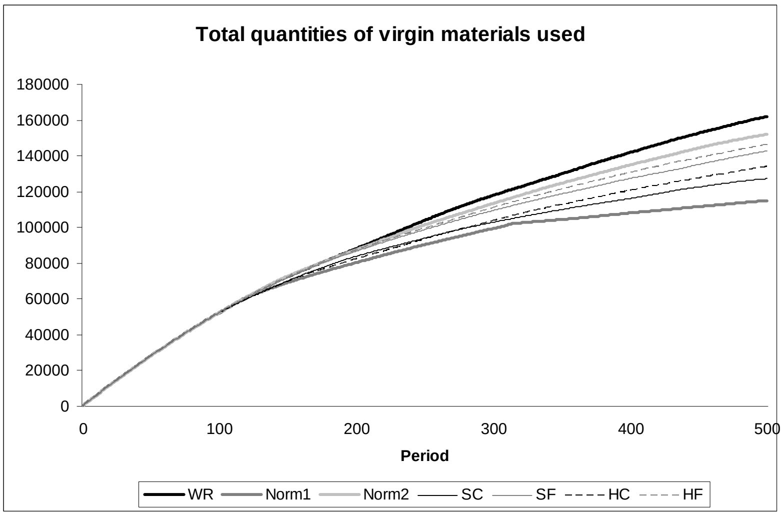
The results emphasize the impact of policy instruments on the evolution of the recycling rate and on the total quantities of virgin materials used (figure 3). It clearly appears that it is the most stringent norm (Norm1) which has the highest environmental impact, since it decreases significantly the quantities of virgin materials and increases the share of recycled waste. These effects are much more moderate with Norm2 which confirms that stringency significantly influences the environmental efficiency of norms. As to the effects of recycling fees, they are more contrasted and very dependent on the design of the instrument. The recycling rate is significantly higher when the fee is specific and paid by consumers (SC), whereas the other designs have no effect. The impact on the use of virgin materials is also more important when the fee is paid by consumers than when it is paid by firms.

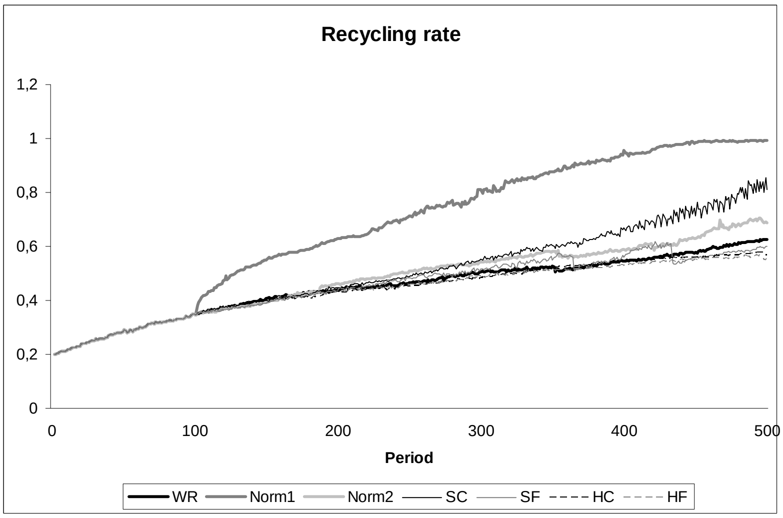
The dynamic efficiency of each policy design can be approached by looking at the trajectories of firms within the product space (figure 4). It is striking to observe that the only cases in which some firms succeed in exploiting efficiently the product space by completely changing their product design and improving recyclability up to the maximum are Norm1 and SC. The difference between both cases is the fact that with Norm1, the best innovative firms also increase the lifetime of their products[19], whereas radical innovations only concern recyclability with SC. The same configuration hold for Norm2 with 3 firms capable of changing their product design, but with a recyclability level lower than the one reached with Norm1 and SC. As to the cases with homogeneous recycling fees (HC and HF), the technological trajectories of firms are not significantly modified comparatively to the case without regulation, which suggests that the dynamic efficiency of those policy designs is very

[18] The number of periods for each simulation is set to 500. Policy instruments are introduced at $t = 100$.
[19] For a discussion of the relative role of recyclability and lifetime of products, see Brouillat (2009a).

low.

Figure 3. Evolution of aggregated environmental variables and market concentration





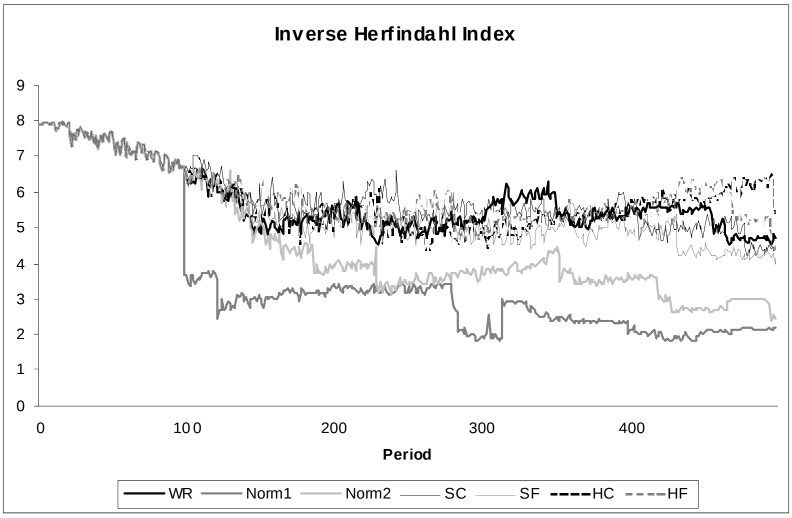
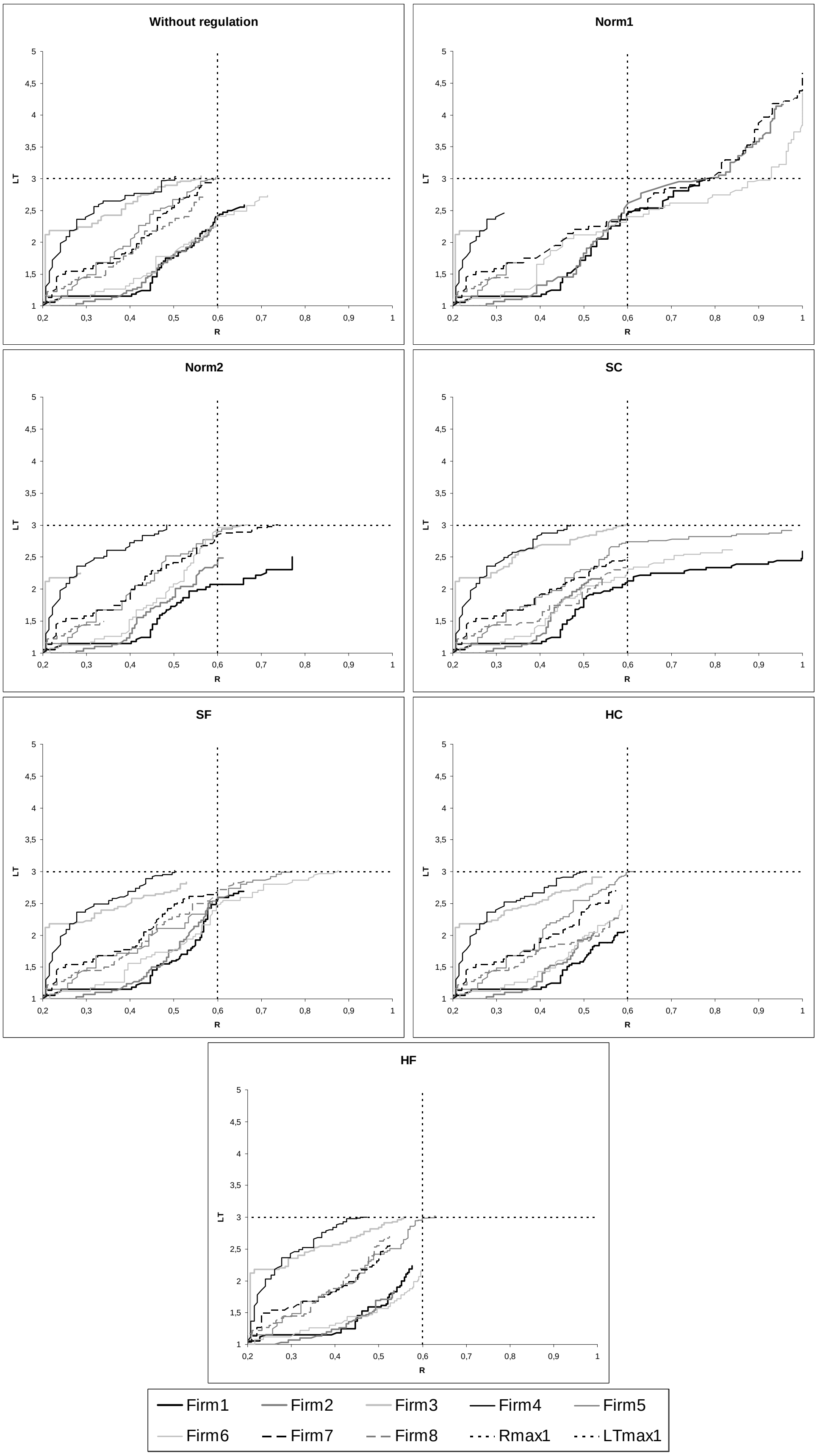


Figure 4. Firms' trajectories in technological space



The results also stress the link between the technological trajectory of firms and their capacity to survive on the market. If we look at individual trajectories, we can observe that in the case of *Norm1,* 4 firms over 8 are not able to comply with the norm and so exit the industry (see table 3 on failure in Appendix). In the long run, only 3 firms survive which explains the trend towards concentration observed on figure 3. In the case of Norm2, 5 firms exit the industry because they cannot bear the costs linked either to the fine either to the radical change in product design (switching costs). The evolution of the Herfindahl index clearly shows that the trend towards concentration is higher in the case of norms than in the case without regulation or with recycling fees. The results underlie that the Schumpeterian trade-off, which is active in the model because of cumulativeness and path-dependency of innovation, is reinforced by the introduction of norms. Recycling norms act as selection mechanisms which strengthen market selection and, in the long run, lead to concentrated oligopolistic structures (cf. figure 3). In the case of recycling fees, the evolution of market concentration is not significantly modified.

3.2. Comparison of policy designs: simulation results with Monte-Carlo procedure

The results presented in table 2 show the impact of the six policy designs considered upon the different variables linked to respectively environmental, dynamic and market efficiency.

The results presented in table 2 are the average value of the selected variables and the results of the Wilcoxon-Mann-Whitney U test: for each instrument, we compare the distribution of each variable with its distribution without regulation (WR)[20].

Globally the results confirm the trends observed in the representative simulation run presented in the previous section. If we first look at each type of instrument separately, regarding fees, we can observe that the highest environmental efficiency is reached with specific recycling fees paid by consumers (SC). When the fee is paid by firms, because of cost constraints, firms have lower profits and so invest less in R&D, which is conducive in the long run to a lower recyclability of products in comparison with the case without regulation. If we concentrate on dynamic efficiency, we can observe a significant positive effect only when the fees are individualized, i.e. specific to firms (SC and SF). In that case, firms invest more R&D on product recyclability, while there is no significant effect when recycling fees are homogenous. This result emphasizes the importance of the policy design and, more particularly, of the rewards and incentives mechanisms. An individualized system of recycling fees enables to reward firms according to the recyclability of their products (the higher the recyclability, the lower the recycling fee), which gives them an incentive to innovate. These results are coherent with the empirical study of Clift and France (2006) which stress that usual take-back systems weaken the incentive effects of this policy, since the most recyclable goods have to support the same recycling fee than the least recyclable ones. It also confirms what is argued by Stevens (2004) according to which it is essential “to have the reward linked directly to efforts on the part of the individual producer and not industry-wide effects”.

[20] Using a significance threshold of 5%, a probability lower than 0,05 means that the values of the two compared samples are different.

Table 2. Simulation results with Monte-Carlo procedure

			Without regulation	Instrument design					
				HC	HF	SC	SF	Norm1	Norm2
Environmental efficiency		Recycling rate	0.485 -	0.483 *0.3201*	0.455 *0.0000*	0.505 *0.0000*	0.464 *0.0000*	0.576 *0.0000*	0.533 *0.0000*
		Total quantities of virgin materials used	188752.3 -	176126.8 *0.0000*	193723.0 *0.0000*	175122.6 *0.0000*	192905.3 *0.0000*	175586.1 *0.0000*	188985.7 *0.8723*
Dynamic efficiency	R&D strategy	Share of R&D on recyclability (δ^R)	0.272 -	0.276 *0.1409*	0.276 *0.0862*	0.387 *0.0000*	0.348 *0.0000*	0.348 *0.0000*	0.347 *0.0000*
		Share of R&D on lifetime (δ^{LT})	0.336 -	0.335 *0.6355*	0.338 *0.6673*	0.293 *0.0000*	0.310 *0.0000*	0.310 *0.0000*	0.307 *0.0000*
		Share of R&D on technical quality (δ^X)	0.393 -	0.390 *0.2749*	0.387 *0.0445*	0.320 *0.0000*	0.345 *0.0000*	0.361 *0.0000*	0.364 *0.0000*
	Product characteristics	Recyclability of products (*R*)	0.411 -	0.407 *0.3191*	0.386 *0.0000*	0.429 *0.0118*	0.390 *0.0000*	0.459 *0.0000*	0.430 *0.0000*
		Lifetime of products (*LT*)	2.040 -	2.004 *0.0101*	1.880 *0.0000*	1.990 *0.0000*	1.872 *0.0000*	2.150 *0.0004*	2.022 *0.0036*
		Technical quality of products (*X*)	0.427 -	0.426 *0.3191*	0.397 *0.0000*	0.421 *0.0118*	0.392 *0.0000*	0.463 *0.0000*	0.423 *0.0059*
	Change in product design	Design for recycling	0.216 -	0.214 *0.6004*	0.188 *0.0000*	0.227 *0.0001*	0.191 *0.0000*	0.403 *0.0000*	0.257 *0.0000*
		Design for durability	0.187 -	0.181 *0.0287*	0.158 *0.0000*	0.180 *0.1333*	0.156 *0.0000*	0.340 *0.0000*	0.219 *0.0040*
		Design for recycling and durability	0.119 -	0.115 *0.1601*	0.100 *0.0000*	0.120 *0.4338*	0.100 *0.0000*	0.279 *0.0000*	0.154 *0.0007*
Market efficiency		Market concentration (inverse Herfindahl index)	6.269 -	6.302 *0.4877*	6.698 *0.0000*	6.113 *0.0085*	6.617 *0.0000*	4.771 *0.0000*	6.009 *0.0000*
		Product price (*p*)	8.880 -	10.892 *0.0000*	9.497 *0.0000*	10.930 *0.0000*	9.507 *0.0000*	8.850 *0.4661*	8.931 *0.2172*
		Firms' profits	332,760 -	327,996 *0.0019*	251,878 *0.0000*	330,085 *0.0086*	251,943 *0.0000*	432.947 *0.0000*	345.463 *0.0397*
		Failure rate of firms	0.163 -	0.163 *0.9390*	0.152 *0.0379*	0.169 *0.2315*	0.154 *0.0850*	0.416 *0.0000*	0.239 *0.0000*

The first row reports the Monte Carlo average value and the second row the Wilcoxon-Mann-Whitney p-value performed on the sample pooled across Monte Carlo simulations

We can stress that a specific fee paid by consumers seems to be the best instrument since it is the only one which entails an increase in product recyclability. Nevertheless we also observe that this positive effect on recyclability is achieved at the detriment of the two other product characteristics on which firms do less R&D. It means that firm specific recycling fees act as focusing devices leading firms to reallocate their R&D investment.

But whatever the policy design, our simulation results also show that a recycling fee cannot encourage firms to radically change their product design. As shown in table 2, the proportion of firms changing the design of their products towards design for recycling and/or durability does not significantly increase whatever the recycling fee system, except the case

SC where the increase is statistically significant but is quite low. It means that the incentive effect on innovation is not sufficient to trigger radical innovations in eco-design activities (even in the SC case). This result is in line with the proposition of Heaton (1997) and Kemp and Pontoglio (2008) according to which the capacity of economic instruments to favour radical technological change is empirically limited.

In terms of market efficiency, it is obvious that recycling fees have a significant impact on prices and that this impact is higher when the fees are paid by consumers. This pressure on prices tends to decrease market demand which explains the decrease in firms' profits. When the recycling fee is paid by firms, the negative impact on profits is higher which also affects the market dynamics and so the level of concentration, even if the failure rate of firms is not significantly modified.

The results on the effects of recycling fees can be summarized by the following proposition:

In order to be efficient in terms of innovation incentives, recycling fees should be specific to firms and proportional to the recyclability of products. Individualized recycling fees paid by consumers seem to be the best compromise in terms of its impact upon innovation and product characteristics. Nevertheless the dynamic efficiency of this type of policy instrument is limited in the sense that it does not bring radical innovations in product design. A trade-off must be found since a recycling fee system entails a significant increase in price and so may affect consumers' surplus.

As to the impact of norms, the results presented in table 2 confirm what we observed in the representative simulation, that is to say that environmental efficiency is higher with Norm1 than with Norm2. The selection of the "greenest" products in the most stringent case leads to a significant decrease in virgin materials flows. In both cases, recycling rate significantly increases and the level of unrecycled waste decreases, but the effects are larger with Norm1.

In terms of R&D and innovation, the results show that the introduction of recyclability norms (whatever the sanction mechanism) entails a significant change in firms' R&D strategy which tends to be more concentrated on product recyclability. This change in R&D strategy effectively leads to a significant improvement in the level of recyclability of products, which means that firms innovate efficiently on this characteristic. The impact of recyclability norms on innovation is all the more significant that we can observe that the proportion of firms changing the design of their products is significantly augmented. These results stress that the introduction of norms is able to entail more frequent changes in product design. So globally, we can say that recyclability norms achieve their objectives in terms of dynamic efficiency.

It is striking to observe that the effects on innovation and product designs are higher in the case of Norm1 than with Norm2, which suggest that the degree of stringency of the norm, in particular the sanction mechanism, is an important determinant of the capacity of the norm to induce radical innovations. This result confirms the idea according to which only stringent command and control instruments can lead to radical innovations, while economic instruments and more flexible regulations tend to trigger mainly incremental innovations and diffusion of existing technologies (Heaton, 1997; Ashford, 2000; Kemp and Pontoglio, 2008). This argument is well illustrated by our model which shows that a stringent norm associated with a sanction mechanism based on market restriction acts as a strong market selection resulting in the "selection of the greenest" and in radical changes in product designs. In this very stringent case, the impact of norms on innovation is due more to a selection effect than to the sole incentive effect.

In our model, this selection effect reinforces the Schumpeterian trade-off by mechanically leading to an increase in profits which enables firms to increase their R&D investment. This result is important to stress that, when there is cumulativeness and increasing returns in innovation, stringent norms can be a way of strengthening cumulativeness and "success breeds success" phenomena. Totally this favours radical innovation and dynamic efficiency, while increasing market concentration. Notably in the most stringent case (Norm1), by acting as a selection device, the norm entails an important increase in the level of concentration and in the failure rate of firms. This can be considered as a negative effect in terms of competition and static efficiency but, on the other hand, norms do not bring about any increase in price which tones down the previous argument.

The results on the impact of recycling norms can be summarized by the following proposition:

By acting as a strong selection device, stringent recycling norms (Norm1) bring about radical innovations in product design and a global improvement in product quality (i.e. over the three characteristics). In terms of environmental and dynamic efficiency, stringent norms appear to be the most efficient instrument.

Table 3 summarizes the relative effects of each policy design.

Table 3. Comparison of instruments

	Norm1	Norm2	SC	SF	HC	HF
Environmental efficiency						
- Recycling rate	++	++	+	-	0	-
- Decrease in quantities of virgin materials used	++	0	++	-	++	-
Dynamic efficiency						
- Share of R&D on recyclability	++	++	++	++	0	0
- Recyclability of products	++	++	++	-	0	-
- Change in product design (design for recyclability)	++	+	+	-	0	-
Market efficiency						
- Market concentration	++	+	0	-	0	-
- Product price	0	0	++	+	++	+
- Firms' profits	++	+	-	--	-	--
- Failure rate of firms	++	+	0	0	0	-

(++ high positive impact, + significant positive impact, 0 no significant impact, -- high negative impact, - significant negative impact)

3.3. Sensitivity analysis to regulation parameters

In this section, we investigate the impact of regulation parameters on the main variables with the help of regression trees[21] (figure 5). A regression tree (Venables and Ripley, 1999) establishes a hierarchy between independent variables using their contributions to the overall fit (R^2) of the regression. The tree gives a hierarchical sequence of conditions on the variables of the model: the higher the role of a condition in the classification of the observed case, the higher its status on the tree. For each condition, the left branch gives the cases for which the condition is true and the right branch gives the cases compatible with the complementary condition[22].

[21] In each regulation case, we only investigate regression trees related to variables significantly impacted by regulation.

[22] For example, in Figure 5-a (Inverse Herfindahl index – Norm1), on the left branch, we have all observations for which $NormRate \geq 0.9143$. On the right branch, we have all observations for which $NormRate < 0.9143$.

Figure 5. Regression trees

Figure 5-a. Regression trees of inverse Herfindahl index

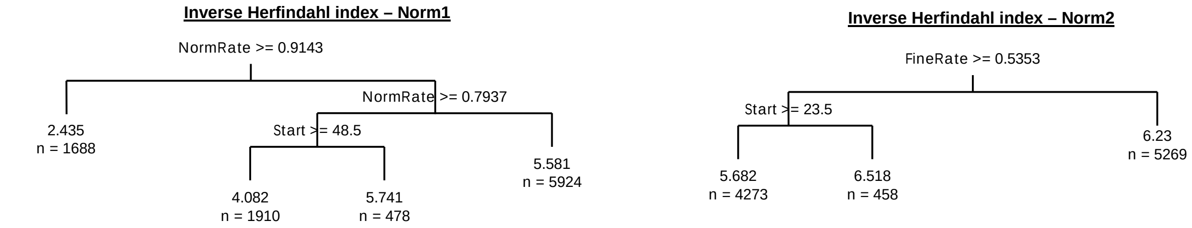


Figure 5-b. Regression trees of product design change (design for recycling)

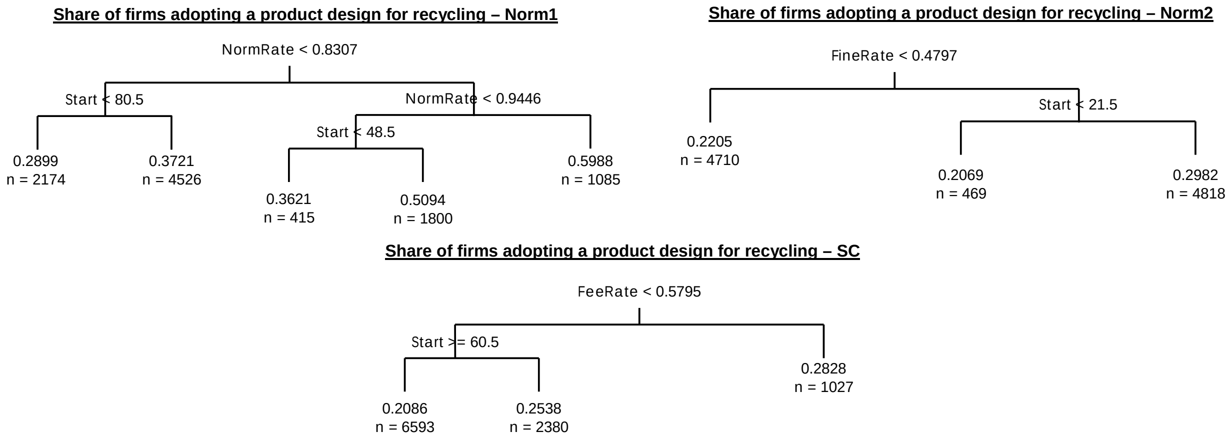
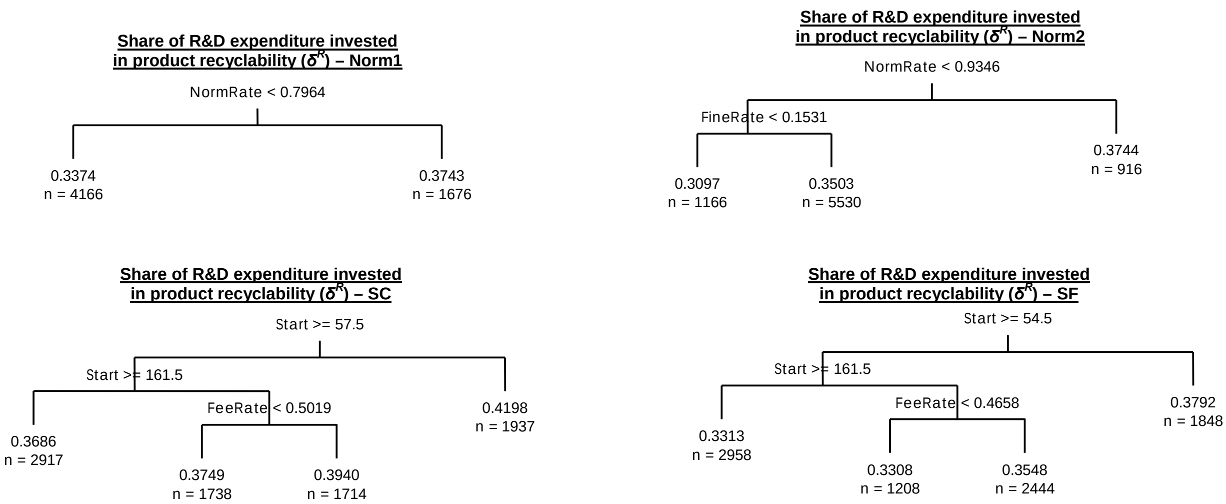
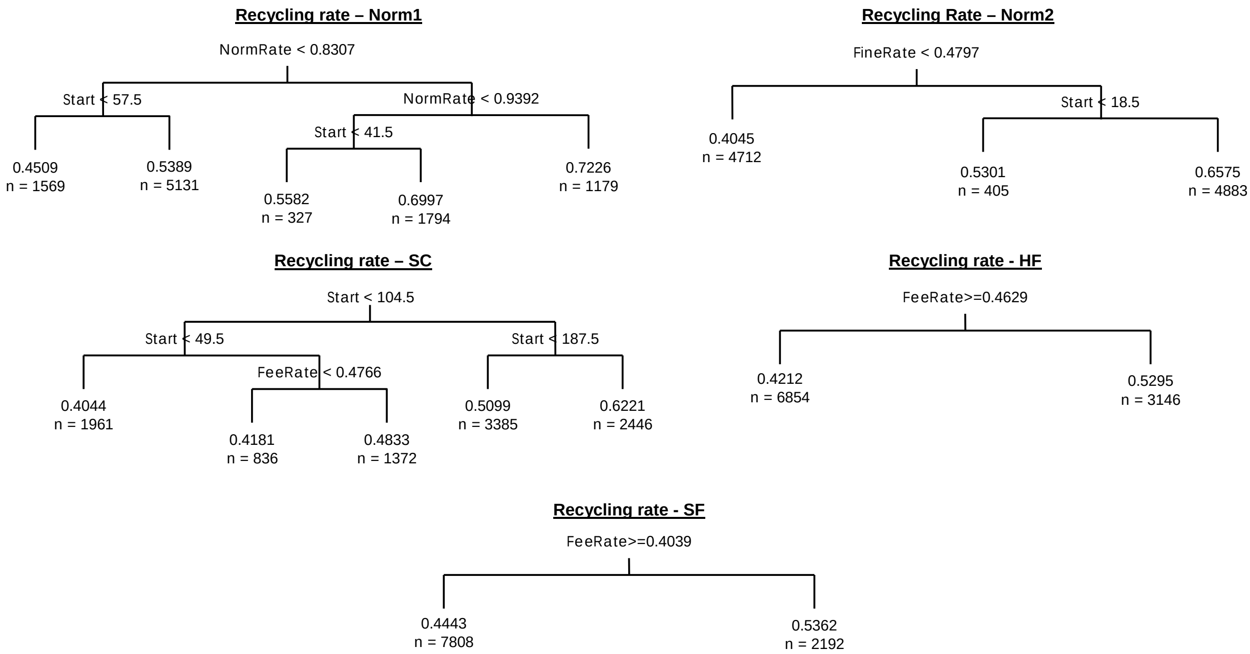


Figure 5-c. Regression trees of firms' R&D strategy (Share invested in product recyclability - δR)



When $0.7937 \leq NormRate < 0.9143$ and $Start \geq 48.5$, the expected value for the inverse Herfindahl index is 4.082 and we have $n = 1910$ observations corresponding to this case.

Figure 5-d. Regression trees of recycling rate



Regression trees enable us to identify the parameters of each policy instrument which are the most influential on the dynamics of the model. For each policy instrument, the degree of stringency, which can be measured by the norm rate as well as by the fine rate and the fee rate, is determining. In the case of Norm1, we observe that the norm rate, which is the parameter determining the level of the recyclability norm (cf. equation 11), determines strongly the impact of the norm on market concentration, on the recycling rate as well as on radical innovation (i.e. share of firms developing a new product design) (cf. figures 5-a, 5-b and 5-d). In the case of Norm2, it is the stringency of the sanction mechanism represented by the fine rate (cf. equation 12) which influences the effects of the norm (cf. figures 5-a, 5-b and 5-d). Globally the more stringent the norms, the higher their environmental and dynamic efficiency.

In the case of recycling fees, if we concentrate on the most efficient design which is SC, we observe that the stringency of the design (high *FeeRate*) tends to increase the impact of the instrument on the recycling rate, on product design change and on the share of R&D on recyclability (cf. figures 5-b to 5-d). Again it suggests that the level of stringency has a positive effect upon environmental efficiency and upon innovative effects of the considered instrument.

Another parameter which appears to be very influential is the date of introduction of the policy instrument (*Start*). In the case of fees, we observe that an early introduction of regulation will favour changes in firms' innovation strategies (figures 5-b and 5-c). But in the case of norms, a later introduction of regulation will have a higher impact on market concentration (figure 5-a) as well as on environmental variables (figure 5-d) and innovation (figure 5-b and 5-c). This result is explained by the way regulation instruments are modelled. When the simulation starts, every firm has the same product recyclability which will increase over time depending on the specific firm's innovation strategy and economic performance. Consequently, the differences in product recyclability tend to increase over time. The effective level of the norm being based on the highest product recyclability on the market (c.f. equation 11), the later the norm comes into play, the more stringent it will be and so the harder it will be for firms to comply with the regulatory requirement. This will tend to increase the number of failures and then market concentration. Surviving firms will then increase their market share and profits leading them to develop more easily an eco-designed product (figure 5-b) which will favour recycling rate (figure 5-d).

These results on the date of introduction of norms are linked to the debate on the timing of environmental policy. The basic question boils down to the question about who is the first to move, the regulator or the firms. As summarized by Requate (2005), a myopic regulator does not anticipate new technology and therefore commits *ex ante* to a level of policy instrument which is optimal given the conventional technology. On the contrary, we speak about *ex post* regulation when the firms move first by engaging in R&D and by innovating in new technology, and the regulator moves second by adapting the level of the policy instrument to the respective R&D outcome. By definition, *ex post* regulation is always time consistent. Even if the literature usually considers the regulator as the natural first mover, more recent contributions show the importance of the regulator's reaction on innovation. Our model confirms that the dynamic efficiency of norms depends on the time of their introduction and that an *ex post* or a late introduction tends to be more efficient because it leaves more time for firms to innovate and improve their technology. With regression trees, we can see that it is the consistency between the stringency of the norm and its date of introduction which determines the final outcome: for example, the impact of a stringent norm on the share of firms developing a product design for recyclability is higher when the norm is introduced later (cf. figure 5-b).

Regression trees also bring statistical support to make comparative tests across policy instruments. They highlight that the efficiency of policy instruments will depend strongly on the value of their parameter settings. Starting from a given parameter setting, a policy instrument which appears to be the more relevant to achieve a given objective can be outperformed by an other policy instrument with a different parameter setting. Regression trees enable us to emphasize some threshold effects and to stress three particular findings:

- In the previous section, norms were found to favour radical change towards eco-designed product. However, we can notice (figure 5-b) that SC-type fees with high minimum level (*FeeRate* ≥ 0.5795) can have the same effect on radical innovations in product design than early introduced Norm1-type norms with a quite low requirement level (*NormRate* < 0.8307 and *Start* < 80.5), and in addition they can be more effective than most configurations of Norm2-type norms;
- When investigating change in firms' innovation strategy towards product recyclability, firm specific fees seem to be in general more incentive than norms, but trees (figure 5-c) highlight that stringent norms (*NormRate* ≥ 0.7964 for Norm1 and *NormRate* ≥ 0.9346 for Norm2) can lead to greater changes than lately introduced specific fees (*Start* ≥ 161.5);
- Regarding environmental performances, norms lead in average to greater recycling rates. Nevertheless, we can notice (figure 5-d) that quite lately introduced SC-type fees (*Start* ≥ 104.5) can be more effective than norms with a quite low stringency level (*NormRate* < 0.8307 for Norm1 and *FineRate* < 0.4797 for Norm2).

To conclude, our results show that it is very difficult to draw general comparative results on the relative efficiency of recycling fees and norms. In particular, the dynamic efficiency of a given policy instrument depends on its parameter settings and on the consistency between stringency and timing. For those reasons, there are some threshold effects such that, under certain parameter settings, a stringent fee system can be more efficient than flexible norms.

4. Conclusion

We developed an original agent-based model to investigate the impacts of recycling fees and norms upon firms' innovative strategy and market structure. This model provides a simplified vision of the problem studied. In fact, many aspects of reality have been intentionally neglected and, needless to say, some hypotheses being assumed here are fairly restricted. However, despite this simplification in the modelling, our simulations yield some interesting conclusions about the effects of policy instruments on industrial dynamics.

Concerning recycling fees, the model dynamics show that only a firm-specific recycling fee, i.e. proportional to the recyclability of each product, would encourage firms to change their R&D strategy towards more recyclable products. A homogeneous fee, i.e. identical for all the firms, will not be an incentive instrument. This result emphasizes that to be efficient incentives must be differentiated across firms in order to take into account technological diversity and to reward the most innovative firms.

Secondly, depending on the distribution of policy costs, i.e. who are the agents paying the fee, the instrument can lead to lower or higher environmental performance. In fact, when firms have to face the fee, product recyclability tends to be lower (because of the negative impact on profits). Ultimately, the model dynamics show that an individualized fee paid by consumers would be the most effective instrument.

More frequent radical changes in product design appear with recyclability norms. Simulation results show that norms encourage firms to shift their innovation strategy towards improvements in the recyclability of their products. They will adopt greener paths leading them to market eco-designed products. These results are in line with the proposal that command and control instruments would be more appropriate when technological improvements require radical innovation (Ashford *et al.*, 1985 ; Ashford, 2000, 2002 ; Taylor *et al.*, 2005 ; Frondel *et al.*, 2007 ; Kemp and Pontoglio, 2008).

Nevertheless, selection mechanisms and incentives introduced with norms will have limited effect on firm innovation strategies because they relate only to offending firms. Once the minimum level of recyclability is achieved, the norm is not a constraint anymore for firms. Moreover due to those selection mechanisms, our results show that implementing a norm reinforces the Schumpeterian trade-off between innovation and market concentration. Since selection will increase market concentration and reduce diversity, only the firms complying with the standard will take full advantage of environmental innovation offsets. Win-win effects (in the sense of Porter and Van der Linde (1995)) will come into play only for those firms, while the others will perceive regulation as a threat.

The model dynamics emphasize that technology responses to regulatory pressure are not simple responses. They involve multiple compromises and trade-offs between the different characteristics of products and will have different impacts on firms' innovative strategy and upon market structure depending on how the policy instrument is formulated and used. Our experiments confirm the proposition of Kemp and Pontoglio (2008) that policy instruments are complex objects and the effects of any policy are linked to the design of the instrument and the context in which it is applied.

References

Ashford N.A., 2000, An Innovation-Based Strategy for a Sustainable Environment. In: Hemmelskamp J., Rennings K. and Leone F. (eds.), *Innovation-Oriented Environmental Regulation: Theoretical Approach and Empirical Analysis*. ZEW-Economic Studies 10, Physica, Heidelberg

Ashford N.A., 2002, Government and environmental innovation in Europe and North America. *American Behavioral Scientist* 45 (9), pp. 1417-1434

Ashford N.A., Ayers C., Stone R.F., 1985, Using Regulation to Change the Market for Innovation. *Harvard Environmental Law Review* 9 (2), pp. 419-466

Brouillat E., 2009a, Recycling and extending product lifetime: an evolutionary modelling, *Journal of Evolutionary Economics* 19 (3), pp. 437-461

Brouillat E., 2009b, An evolutionary model of recycling and product lifetime extension, *Technological Forecasting and Social Change* 76 (4), pp. 471-486

Calcott P; Wall M., 2005, "Waste, recycling and design for environment: roles for markets and policy instruments", *Resource and Energy Economics,* Vol.27(4), pp.287-305

Clift R., France C., 2006, Extended Producer Responsibility in the EU: A Visible March of Folly. *Journal of Industrial Ecology* 10 (4), pp. 5-7

Dosi, G., 1988, 'The nature of the innovative process', in *Technical change and economic theory*, G. Dosi, C. Freeman, R. Nelson, G. Silverberg and L. Soete (eds), Pinter Publishers, London and New York, pp.221-238.

Frondel M., Horbach J., Rennings K., 2007, End-of-Pipe or Cleaner Production? An Empirical Comparison of Environmental Innovation Decisions Across OECD Countries. *Business Strategy and the Environment* 16 (8), pp. 571-584

Fullerton D. Wu W., 1998, "Policies for green design", *Journal of Environmental Economics and Management,* Vol.36(2), pp.131-148

Heaton G., 1997, *Environmental Policies and Innovation: An Initial Scoping Study*. OECD Report prepared for the OECD Environment Directorate and Directorate for Science, Technology and Industry

Janssen M., Jager W., 2002, Stimulating diffusion of green products - Co-evolution between firms and consumers. *Journal of Evolutionary Economics* 12 (3), pp. 283-306

Kemp R., Pontoglio S., 2008, The innovation effects of environmental policy instruments – a typical case of the blind men and the elephant. Paper for DIME WP 2.5 Workshop on Empirical Analyses of Environmental Innovations, ISI, Karlsruhe, January, 17th-18th, 2008

Kneeze A. Schulze C., 1975, *Pollution, Prices and Public Policy*, Brookings, Washington D.C.

Leibenstein H., 1976, *Beyond Economic Man. A New Foundation For Microeconomics*, Cambridge, MA, Harvard University Press

Malerba F., Nelson R., Orsenigo L., Winter S., 1999, « History-friendly » models of industry evolution: the computer industry. *Industrial and Corporate Change* 8 (1), pp. 3-40

Malerba F., Nelson R., Orsenigo L., Winter S., 2007, Demand, innovation and the dynamics of market structure: the role of experimental users and diverse preferences. *Journal of Evolutionary Economics* 17 (4), pp. 371-399

Malerba F., Nelson R., Orsenigo L., Winter S., 2008, Public policies and changing boundaries of firms in a "history-friendly" model of the co-evolution of the computer and semiconductor industries. *Journal of Economic Behavior & Organization* 67 (2), pp. 355–380

Mayers K., 2007, Strategic, Financial, and Design Implications of Extended Producer Responsibility in Europe: A Producer Case Study. *Journal of Industrial Ecology* 11 (3), pp. 113-131

OCDE, 2006, *Working Group on Waste Prevention and Recycling - EPR Policies and Product Design: Economic Theory and Selected Case Studies*. Environment Directorate, Environment Policy Committee, ENV/EPOC/WGWPR(2005)9/FINAL, OECD, Paris

Palmer K. and Walls M., 1997, "Optimal policies for solid waste disposal: taxes, subsidies and standards", *Journal of Public Economics,* Vol.65, pp.193-205

Porter M.E., van der Linde C., 1995, Toward a New Conception of the Environment-Competitiveness Relationship. *Journal of Economic Perspectives* 9 (4), pp. 97-118

Requate T., 2005, "Dynamic incentives by environmental policy instruments – a survey", *Ecological Economics,* Vol. 54, pp.175-195.

Silverberg G., Verspagen B., 1995, Evolutionary theorizing on economic growth. In: Dopfer K. (ed.) *The Evolutionary Principles of Economics*. Norwell, MA, Kluwer Academic Publishers

Stevens C., 2004, Extended Producer Responsibility and Innovation, in *Economic Aspects of Extended Producer Responsibility,* OECD, 2004, pp. 199-219

Taylor M.R., Rubin E.S., Hounshell D.A., 2005, Control of SO_2 emissions from power plants: A case of induced technological innovation in the U.S. *Technological Forecasting and Social Change* 72 (6), pp. 697-718

Venables W., Ripley B.D., 1999, *Modern Applied Statistics with S-PLUS*. Third edition. Springer, New York

Walls M., 2004, The Role of Economics in Extended Producer Responsibility: Making Policy Choices and Setting Policy Goals, in *Economic Aspects of Producer Responsibility,* (Organization for Economic Cooperation and Development (OECD), Paris, June 2004.

Appendix

Table 1. Chosen domain for the most important parameters in the Monte Carlo procedure

	Parameter/Variable	Initial value	Description
Market	N	[5 ; 15]	Initial number of firms
	Xmax	1	Maximum technical quality
	LTmax1	[1 ; 5]	Maximum product-life with initial product design
	Rmax1	[0.2 ; 1]	Maximum recyclability with initial product design
	LTmax2	5	Maximum product-life with eco-design
	Rmax2	1	Maximum recyclability with eco-design
	AC^{LT}	[200 ; 600]	Switching cost related to the adoption of a product design for durability
	AC^{R}	[200 ; 600]	Switching cost related to the adoption of a product design for recycling
	$Length\_AC^{LT}$	[10 ; 30]	Number of periods over which a switching cost must be borne when the firm adopts a product design for durability
	$Length\_AC^{R}$	[10 ; 30]	Number of periods over which a switching cost must be borne when the firm adopts a product design for recycling
	pr	[3 ; 6]	Price of recycled inputs
	pv	[3 ; 6]	Price of virgin inputs
Firm	λ	1	Mark-up
	X	0.2	Initial technical quality
	LT	1	Initial product-life
	R	0.2	Initial recyclability
	μ	[0.1 ; 0.2]	Share of profits invested in R&D
	$\delta^X, \delta^{LT}, \delta^R$	[0 ; 1] with $\delta^X + \delta^{LT} + \delta^R = 1$	Initial share of R&D expenditure invested respectively in product technical quality improvement, in product-life extension and in product recyclability improvement
	η	[0 ; 1]	Rate at which the research level adjusts the R&D expenditure of the current period
	$\gamma_1, \gamma_2, \gamma_3$	[0 ; 1] with $\gamma_1 + \gamma_2 + \gamma_3 = 1$	Impact, respectively, of the research level, of the exhaustion in innovation opportunities, of the cumulated experience and on the improvement of the considered characteristic
	k	0.03	Maximum probability to change innovation strategy
	Imitate	0.97	Propensity to imitate the strategy of competitors
Consumer	GreenShare	Drawn from the normal distribution N(0.25 ; 0.2)	Share of green consumers
	$\beta_1, \beta_2, \beta_3$	[0 ; 1] with $\beta_1 + \beta_2 + \beta_3 = 1$ $\beta_1 < \beta 3$ for green consumers $\beta_1 > \beta 3$ for non-green consumers	Sensitivity of the products' visibility towards respectively product technical quality, inverse product use cost and product recyclability
	β_4	[0 ; 0.5]	Sensitivity of the products' visibility towards product market share
	x	[0.35 ; 0.95]	Maximum obsolescence probability
Recycler	μ_{rec}	[0.1 ; 0.2]	Share of recycler profits invested in R&D
	δ_{rec}	[0 ; 1]	Share of recycler R&D expenditure to improve the quality of recycled materials
	CF_{rec}	[150 ; 450]	Recycler's fixed costs
	c_{rec}	3	Initial value for recycler's marginal cost
Regulation	Start	[1 ; 250]	Period the regulation comes into force
	FeeRate	[0.4 ; 0.6]	Minimum value for the recycling fee
	NormRate	[0.5 ; 1]	Parameter reflecting the level of norm
	FineRate	[0 ; 1]	Parameter reflecting the level of fine

Table 2. Chosen value for parameters of the single simulation run

	Parameter/Variable	Initial value	Description
Market	N	8	Initial number of firms
	Xmax	1	Maximum technical quality
	LTmax1	3	Maximum product-life with initial product design
	Rmax1	0.6	Maximum recyclability with initial product design
	LTmax2	5	Maximum product-life with eco-design
	Rmax2	1	Maximum recyclability with eco-design
	AC^{LT}	300	Switching cost related to the adoption of a product design for durability
	AC^{R}	300	Switching cost related to the adoption of a product design for recycling
	$Length\_AC^{LT}$	15	Number of periods over which a switching cost must be borne when the firm adopts a product design for durability
	$Length\_AC^{R}$	15	Number of periods over which a switching cost must be borne when the firm adopts a product design for recycling
	pr	4.5	Price of recycled inputs
	pv	4.5	Price of virgin inputs
Firm	λ	1	Mark-up
	X	0.2	Initial technical quality
	LT	1	Initial product-life
	R	0.2	Initial recyclability
	μ	0.2	Share of profits invested in R&D
	δ^{X}	Firm 1 and 2: 0.2 Firm 3 and 4: 0.2 Firm 5 and 6: 0.6 Firm 7 and 8: 0.334	Initial share of R&D expenditure invested in product technical quality improvement
	δ^{LT}	Firm 1 and 2: 0.2 Firm 3 and 4: 0.6 Firm 5 and 6: 0.2 Firm 7 and 8: 0.333	Initial share of R&D expenditure invested in product-life extension
	δ^{R}	Firm 1 and 2: 0.6 Firm 3 and 4: 0.2 Firm 5 and 6: 0.2 Firm 7 and 8: 0.333	Initial share of R&D expenditure invested in product recyclability improvement
	η	0.5	Rate at which the research level adjusts the R&D expenditure of the current period
	γ_1	0.6	Impact of the research level on the improvement of the considered characteristic
	γ_2	0.3	Impact of the exhaustion in innovation opportunities on the improvement of the considered characteristic
	γ_3	0.1	Impact of the cumulated experience on the improvement of the considered characteristic
	k	0,03	Maximum probability to change innovation strategy
	Imitate	0,97	Propensity to imitate the strategy of competitors
Consumer	GreenShare	0.1	Share of green consumers
	β_1	0.6 for green consumers 0.1 for non-green consumers	Sensitivity of the products' visibility towards product technical quality
	β_2	0.3	Sensitivity of the products' visibility towards inverse product use cost
	β_3	0.1 for green consumers 0.6 for non-green consumers	Sensitivity of the products' visibility towards product recyclability
	β_4	0.25	Sensitivity of the products' visibility towards product market share
	x	0.5 for green consumers 0.8 for non-green consumers	Maximum obsolescence probability
Recycler	μ_{rec}	0.2	Share of recycler profits invested in R&D
	δ_{rec}	0.5	Share of recycler R&D expenditure to improve the quality of recycled materials
	CF_{rec}	300	Recycler's fixed costs
	c_{rec}	3	Initial value for recycler's marginal cost
Regulation	Start	100	Period the regulation comes into force
	FeeRate	0.45	Minimum value for the recycling fee
	NormRate	0.75	Parameter reflecting the level of norm
	FineRate	0.65	Parameter reflecting the level of fine

Table 3. Firms failures in the single simulation run

	Firm 1	Firm 2	Firm3	Firm 4	Firm 5	Firm 6	Firm 7	Firm 8
SR			t = 466 *LTmax1 crossing*	t = 225 *LTmax1 crossing*	t = 360 *LTmax1 crossing*			
Norm1	t = 290 *LTmax1 crossing*		t = 101 *norm*	t = 101 *norm*	t = 101 *norm*			t = 101 *norm*
Norm2			t = 187 *fine*	t = 239 *LTmax1 crossing*	t = 363 *LTmax1 crossing*	t = 429 *LTmax1 crossing*		t = 165 *fine*
HC				t = 241 *LTmax1 crossing*				
HF			t = 479 *LTmax1 crossing*	t = 291 *LTmax1 crossing*				
SC			t = 415 *LTmax1 crossing*	t = 253 *LTmax1 crossing*			t = 479 *Rmax1 crossing*	
SF				t = 292 *LTmax1 crossing*	t = 373 *LTmax1 crossing*	t = 442 *LTmax1 crossing*		

t: time period at which the firm exits the market

Failure causes:

LTmax1 crossing: negative profits because of the adoption costs the firm has to face when it crosses the threshold LTmax1 and changes its product design to develop a long lifetime product

Rmax1 crossing: negative profits because of the adoption costs the firm has to face when it crosses the threshold Rmax1 and changes its product design to develop a highly recyclable product

norm: the firm must exit the market because its product recyclability is lower than the norm

fine: negative profits because of the fine the firm must pay since its product recyclability is lower than the norm

Cahiers du GREThA
Working papers of GREThA

GREThA UMR CNRS 5113

Université Montesquieu Bordeaux IV
Avenue Léon Duguit
33608 PESSAC - FRANCE
Tel : +33 (0)5.56.84.25.75
Fax : +33 (0)5.56.84.86.47

http://gretha.u-bordeaux4.fr/

Cahiers du GREThA (derniers numéros)

2010-19 : BONIN Hubert, *French investment banks and the earthquake of post-war shocks (1944-1946)*
2010-20 : BONIN Hubert, *Les banques savoyardes enracinées dans l'économie régionale (1860-1980s)*
2011-01 : PEREAU Jean-Christophe, DOYEN Luc, LITTLE Rich, THEBAUD Olivier, *The triple bottom line: Meeting ecological, economic and social goals with Individual Transferable Quotas*
2011-02 : PEREAU Jean-Christophe, ROUILLON Sébastien, *How to negotiate with Coase?*
2011-03 : MARTIN Jean-Christophe, POINT Patrick, *Economic impacts of development of road transport for Aquitaine region for the period 2007-2013 subject to a climate plan*
2011-04 : BERR Eric, *Pouvoir et domination dans les politiques de développement*
2011-05 : MARTIN Jean-Christophe, POINT Patrick, *Construction of linkage indicators of greenhouse gas emissions for Aquitaine region*
2011-06 : TALBOT Damien, *Institutions, organisations et espace : les formes de la proximité*
2011-07 : DACHARY-BERNARD Jeanne, GASCHET Frédéric, LYSER Sandrine, POUYANNE Guillaume, VIROL Stéphane, *L'impact de la littoralisation sur les valeurs foncières et immobilières: une lecture différenciée des marchés agricoles et résidentiels*
2011-08 : BAZEN Stephen, MOYES Patrick, *Elitism and Stochastic Dominance*
2011-09 : CLEMENT Matthieu, *Remittances and household expenditure patterns in Tajikistan: A propensity score matching analysis*
2011-10 : RAHMOUNI Mohieddine, YILDIZOGLU Murat, *Motivations et déterminants de l'innovation technologique : Un survol des théories modernes*
2011-11 : YILDIZOGLU Murat, SENEGAS Marc-Alexandre, SALLE Isabelle, ZUMPE Martin, *Learning the optimal buffer-stock consumption rule of Carroll*
2011-12 : UGAGLIA Adeline, DEL'HOMME Bernard, FILIPPI Maryline, *Overcoming grape growers'pesticide lock-in*
2011-13 : BOURDEAU-LEPAGE Lise, GASCHET Frédéric, LACOUR Claude, PUISSANT Sylvette, *La métropolisation 15 ans après*
2011-14 : BROUILLAT Eric, OLTRA Vanessa, *Dynamic efficiency of Extended Producer Responsibility (EPR) instruments in a simulation model of industrial dynamics*

La coordination scientifique des Cahiers du GREThA est assurée par Sylvie FERRARI et Vincent FRIGANT. La mise en page est assurée par Dominique REBOLLO