Environmental policy instruments for waste prevention in a simulation model of industrial dynamics

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ABSTRACT

This paper presents an original approach to the impact of environmental policy 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). We use the same simulation model 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 which are recycling fees on the one hand, and norms on the other. 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.

JEL Classification: O33, D21, Q53

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. This article sheds light on this question by studying the impact of different EPR policy instruments on firms' innovative strategies and on the evolution of 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). Brouillat (2009a, b) develops a micro-simulation model enabling us 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 contribution of this model is to introduce recyclability as a main characteristic of products, to study the interactions with the other characteristics and to integrate endogenous recycling activities and raw materials flows.

In this paper, we use the same model 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 which are recycling fees on the one hand, and norms on the other. For each instrument, we will consider different policy designs in order to study their effects on industrial dynamics. The main contribution of the 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 a firm’s market share. 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 considered policy instruments shape market selection.

The paper is organized as follows. In section 2 we present the model. In section 3 we present simulation results and we discuss the impact of policy instruments 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

We present an evolutionary simulation model that studies the co-evolution of industrial and environmental dynamics in the field of waste management. Our multi-agent model describes the behaviour of firms as well as that of consumers and recyclers.

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 environmental regulation on the development of green 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 predictions. 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). 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[1].

We consider the market of a generic durable product. We take into account three categories of actors: firms all marketing a single finished product (*i*)[2], end 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.

- *Product quality*

Product quality is divided into three dimensions: recyclability (*R*), durability (*LT*) and technical quality (*X*). It was presumed that there is a maximum recyclability threshold (*Rmax1)* and a lifetime threshold (*LTmax1)* characterizing the design change needed to increase product recyclability and lifetime. This means that *Rmax1* and *LTmax1* represent the maximum recyclability and lifetime reachable through incremental innovations. Crossing these thresholds requires completely reviewing product design in order to take into account its end-of-life from the design phase. Thus, any firm will be able to exceed *Rmax1* and/or *LTmax1* only by offering a new product based on a new design. As to the technical characteristics *(X)*, it reflect its "conventional" quality. This 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. *X* is limited by a fixed upper limit *Xmax* reflecting the maximal performance on this dimension.

On the demand side, 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 this product do not satisfy their expectations anymore. The modelling of these renewal decisions is based on obsolescence probabilities depending on a comparison between the best and the worst technical quality (*X)* of the product currently used by consumers on the market in the current period.

Figure 1 represents the product quality space in which each firm will be characterised (according to its innovative activities) by a technological trajectory. In fact, each firm will improve the quality of its product on one or several dimensions to make it more attractive towards consumers. These improvements and the direction of firm's trajectory will depend on its R&D strategy. Adopting a new product design[3] necessitates time and money, so that

[1] Interested readers may obtain a full copy of the simulation model by writing to the authors.

[2] Consequently, *i* represents the product as well as the producer.

[3] i.e. when the firm's product lifetime and/or recyclability become greater than *LTmax1* and/or *Rmax1*.

changing product design requires a transition period over which the firm will face additional costs (Malerba et al, 1999).

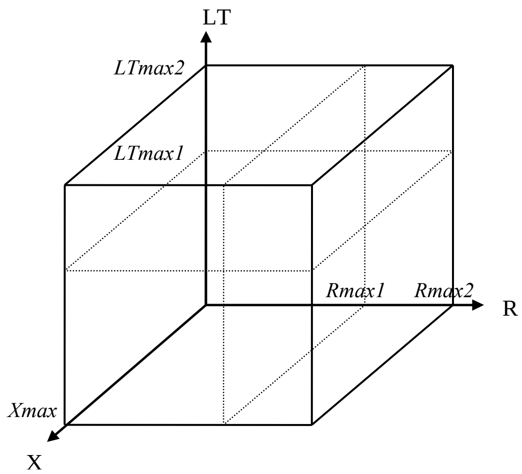

Fig.1. Product's quality attributes

As soon as a new product design is adopted, the firm enters in an adoption phase over which an adoption cost will have to be borne. These costs will be borne by firms over several periods following the adoption and consequently, it will lower profits[4]. Net profits (Π) are then equal to gross profits minus adoption costs the firm has to face. These net profits play the role of financial constraint by determining the budget allocated to R&D. Firms exit the market if they make losses (negative net profits) over at least ten consecutive periods.

- Innovation process

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):

$$RD_{i,t}^{X} = \delta_{i,t}^{X}.RD_{i,t} \quad (1.a)$$

$$RD_{i,t}^{LT} = \delta_{i,t}^{LT}.RD_{i,t} \quad (1.b)$$

$$RD_{i,t}^{R} = \delta_{i,t}^{R}.RD_{i,t} \quad (1.c)$$

The firm specific variables δ^X, δ^{LT} and δ^R reflect the firm's distribution choice of R&D expenditure and, consequently, its innovation strategy regarding product's characteristics.

[4] Additional costs and the duration of payment are identical for all the firms.

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

$$S_{i,t}^{X} = \eta.RD_{i,t}^{X} + (1-\eta).S_{i,t-1}^{X} \quad (2.a)$$

$$S_{i,t}^{LT} = \eta.RD_{i,t}^{LT} + (1-\eta).S_{i,t-1}^{LT} \quad (2.b)$$

$$S_{i,t}^{R} = \eta.RD_{i,t}^{R} + (1-\eta).S_{i,t-1}^{R} \quad (2.c)$$

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. In fact, knowledge level determines the probabilities of access to new values within the range of product characteristics. 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:

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

This equation implies that the value of 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 with a specific product design). The same applies to product lifetime and recyclability[5].

In Brouillat (2009a, b), R&D strategies are fixed. 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. 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. Only the firms with unsatisfactory profit levels will choose to change their strategy. This assumption reflects the satisficing behaviour of firms linked to the context of bounded rationality. Firms will decide then to change their R&D strategy with probabilities proportional to their gross profits and the best and the worst profits observed on the market in the current period (*Πmax* and *Πmin*):

[5] This formulation is inspired from Malerba and al. (1999, 2007).

$$\Pr ob_{i,t}^{Change} = k.\left(1 - \frac{\Pi_{i,t} - \Pi \min_t}{\Pi \max_t - \Pi \min_t}\right) \quad (4)$$

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[6]:

- 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].

- Supply-demand interactions

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*)[7]:

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

The visibility of the product is a specification of its total performance. 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 (price per period of use) and recyclability. *MS* is the market share of the firm and the parameter β_4 reflects the bandwagon effect. The parameters β_1, β_2, β_3 and β_4 represent, then, the consumer's preferences with respect to the product's characteristics[8].

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

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

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 ($\tilde{L}T$ and $\tilde{R}$) and that these perceptions result from random draws in a normal distribution centred on the actual values.

- The recycler

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. He collects the complete range of end of life products which he recycles, depending on the recyclability (R) of these products[9], and sells to the firms as recycled inputs[10]. Then 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[11]. 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 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.

2.2. Modelling recycling fees and norms

The main contribution of this model is to simulate the impact of two policy instruments for waste prevention. 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. In other words, policy makers are seen as external actors and environmental policy is understood only through the impact of regulatory instruments on the system. We assume that public authorities are fully informed about the

[9] Starting from a unit of end of life product, the recycler manufactures and sells R units of recycled inputs.
[10] We are assuming that the part which cannot be recycled is incinerated or stocked in a waste disposal site.
[11] 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.).

performance level of firms and so are able to control and to monitor them to ensure that regulation is fully respected.

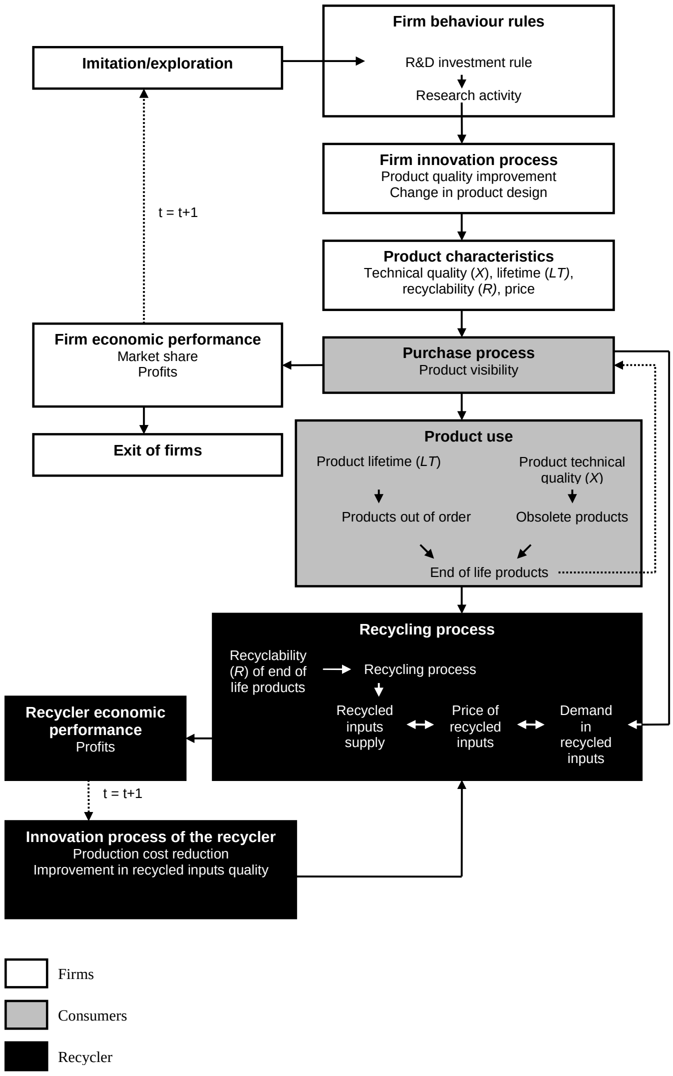

Fig.2. Model structure

Two types of waste prevention instruments, which lie under the EPR umbrella, are considered: recycling fees and norms. Each type of instrument is introduced into the system at a more or less early given time *T* chosen randomly for each simulation. Both instruments contribute to the same multiple objectives: reduction in waste volume and in virgin materials use, increase in eco-design activities, and development of the recycling sector.

- Recycling fees

The main policy instruments of extended producer responsibility (EPR) is end-of-life product take-back mandates (OECD, 2006). In order to cope with this 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[12].

In order to model this type of instrument, 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 the second case, the fee is specific to firms, i.e. proportional to the recyclability of the products sold by each firm. The recycling fee is in the meantime an extra cost for firms and an additional financial resource for the recycler. 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.

In this perspective, we study 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).

Such recycling norms are introduced in a very simple way in our model. The level of the recyclability norm (*Rmin*) is settled between the initial product recyclability and maximum recyclability. 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

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

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.

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 the following section.

3. The impact of policy instruments on innovation and selection: 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 the way it is implemented, and more particularly according to its stringency *versus* flexibility and its time frame. The effects of each policy instrument mainly depend on its design and on the way it is implemented. It is in this perspective that we consider different rules or designs for each instrument. Moreover each instrument is evaluated in relation to its multiple objectives i.e. reduction in waste volume and in virgin materials use, increase in eco-design activities and so in innovation, and finally development of the recycling sector.

The results presented in this section come 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. It is a way of exploring the whole space of parameters and of emphasizing the variety of the possible outcomes of the model without an arbitrary initialization of the parameters.

The results presented in tables 1 and 2 are the average value of some selected variables (affected by the policy instruments) and the results of Student T test or Wilcoxon-Mann-Whitney U test: for each instrument, we compare the distribution of each variable with its distribution without regulation (WR) using these tests[13]. We also present in tables 1 and 2 the

[13] We use Student T test for the failure rate and product design change. We use Wilcoxon-Mann-Whitney U test for all the other variables.

probability of the test: using a significance threshold of 5%, a probability lower than 0.05 means that the values of the two compared samples tend to be different.

3.1. Simulation results on the effects of recycling fees

The results presented in table 1 show the impact of the four types of recycling fees on market structure and price, on firms' R&D strategy, on product characteristics and design change (proportion of firms changing the design of their products), on environmental characteristics and on the recycler's profits. This set of variables describes thoroughly the different effects of the considered policy designs.

The results show that recycling fees have a significant impact on prices and, obviously, 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. Concerning the effects on R&D and innovation, 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.

Moreover we can observe 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 (cf. fig.3). 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. We can argue that firm specific recycling fees act as focusing devices leading firms to reallocate their R&D investment.

In spite of the positive effect upon R&D strategy, it is striking to note that a specific fee paid by firms has a negative impact on product recyclability, and so does not reach its main objective, because of the consecutive cost constraint and decrease in profits.

		Without regulation	Instrument design			
			HC	HF	SC	SF
Concentration (inverse Herfindahl index)		6.269 -	6.302 *0.4877*	6.698 *0.0000*	6.112 *0.0085*	6.617 *0.0000*
Failure rate		0.163 -	0.163 *0.9390*	0.152 *0.0379*	0.169 *0.2315*	0.154 *0.0850*
Product price (*p*)		8.880 -	10.892 *0.0000*	9.497 *0.0000*	10.930 *0.0000*	9.507 *0.0000*
Firm profits (*Π*)		332,760 -	327,996 *0.0019*	251,878 *0.0000*	330,085 *0.0086*	251,943 *0.0000*
R&D strategy	Share invested in product technical quality (δ^X)	0.393 -	0.390 *0.2749*	0.387 *0.0445*	0.320 *0.0000*	0.345 *0.0000*
	Share invested in product recyclability (δ^R)	0.272 -	0.278 *0.1409*	0.273 *0.0862*	0.385 *0.0000*	0.346 *0.0000*
	Share invested in product lifetime (δ^{LT})	0.336 -	0.335 *0.6355*	0.338 *0.6673*	0.293 *0.0000*	0.307 *0.0000*
Product characteristics	Technical quality (*X*)	0.427 -	0.426 *0.3191*	0.397 *0.0000*	0.421 *0.0118*	0.392 *0.0000*
	Recyclability (*R*)	0.411 -	0.407 *0.3191*	0.386 *0.0000*	0.429 *0.0118*	0.390 *0.0000*
	Lifetime (*LT*)	2.040 -	2.004 *0.0101*	1.880 *0.0000*	1.990 *0.0000*	1.872 *0.0000*
Product design change[14]	Design for recycling	0.212 -	0.205 *0.1747*	0.188 *0.0000*	0.221 *0.1644*	0.197 *0.0063*
	Design for durability	0.199 -	0.199 *0.8595*	0.168 *0.0000*	0.195 *0.3463*	0.165 *0.0000*
	Design for recycling and durability	0.085 -	0.084 *0.7411*	0.072 *0.0005*	0.089 *0.3043*	0.074 *0.0048*
Environmental variables	Part of recycled inputs	0.424 -	0.543 *0.0000*	0.546 *0.0000*	0.557 *0.0000*	0.555 *0.0000*
	Waste streams	611.181 -	562.104 *0.0000*	642.414 *0.0000*	567.313 *0.0000*	642.708 *0.0000*
	Virgin materials flows	371.043 -	326.633 *0.0000*	392.327 *0.0000*	319.275 *0.0000*	386.809 *0.0000*
Recycler profit		111.089 -	1250.249 *0.0000*	1540.183 *0.0000*	1294.352 *0.0000*	1575.339 *0.0000*

Table 1. The effects of recycling fees

[14] It returns the share of firms which have changed their product design. It is based on all the firms: those still on the market and those which have already left the market.

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 1, the proportion of firms changing the design of their products towards design for recycling and/or durability is not affected by the recycling fee system. 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.

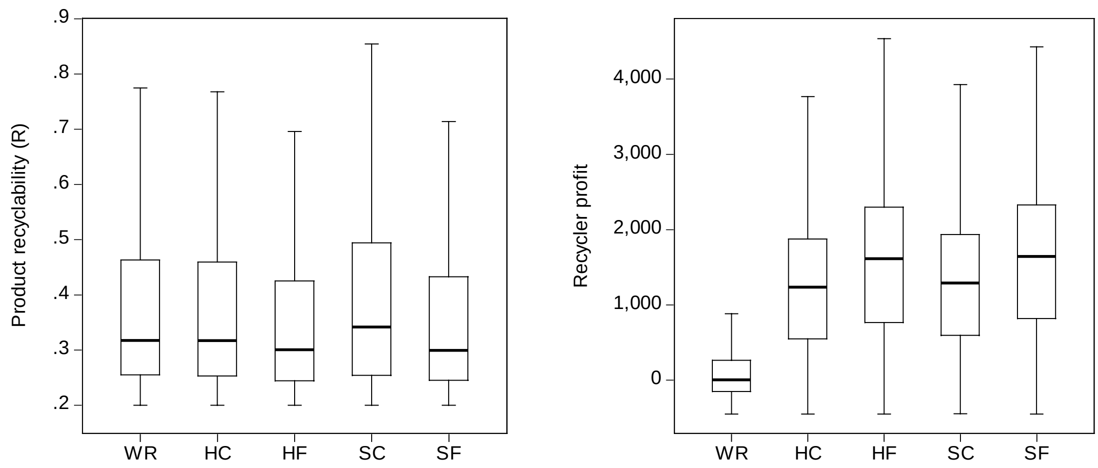

Fig.3. Distribution (box-plots) of product recyclability and recycler's profits

The impact on environmental indicators, i.e. recycled inputs, waste streams and virgin material flows, is globally significant and positive (but rather moderate) for all policy designs. As to the last objective of this type of policy instruments, which is to support the development of the recycling sector, we can see that the objective is globally satisfied since recycler's profits are significantly higher (cf. fig.3).

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.

3.2. Simulation results on the impact of norms

The results presented in table 2 emphasize that norms have a strong impact on 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 (cf. fig.4) and in the failure rate of firms. This can be considered as negative effect in terms of competition and static efficiency. On the other hand, norms do not bring about any increase in price which relativize the previous argument.

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 (cf. fig.4), 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 mechanically leads to an increase in profits which enables firms to increase their R&D investment. Given that this effect is much higher with Norm1, firms can increase globally their R&D budget and so innovate on the three product characteristics, while with Norm2 the increase in profits is so that firms can only improve the recyclability of their product at the expense of the two other characteristics.

As to environmental indicators, again the results show that impacts are higher with Norm1 than with Norm2. The selection of the greenest in the most stringent case leads to a significant decrease in waste streams and virgin materials flaws. In both cases, recycling rate significantly increases and the level of unrecycled waste decreases, but the effects are larger with Norm1 (cf. fig.6 in Appendix).

		Without regulation	Instrument design	
			Norm1	Norm2
Concentration (inverse Herfindahl index)		6.269 -	4.771 *0.0000*	6.009 *0.0000*
Failure rate		0.163 -	0.416 *0.0000*	0.239 *0.0000*
Product price (*p*)		8.880 -	8.850 *0.4661*	8.931 *0.2172*
Firm profits (*Π*)		332,760 -	432.947 *0.0000*	345.463 *0.0397*
R&D strategy	Share invested in product technical quality (δ^X)	0.393 -	0.361 *0.0000*	0.364 *0.0000*
	Share invested in product recyclability (δ^R)	0.272 -	0.348 *0.0000*	0.347 *0.0000*
	Share invested in product lifetime (δ^{LT})	0.336 -	0.310 *0.0000*	0.307 *0.0000*
Product characteristics	Technical quality (*X*)	0.427 -	0.463 *0.0000*	0.423 *0.0059*
	Recyclability (*R*)	0.411 -	0.459 *0.0000*	0.430 *0.0000*
	Lifetime (*LT*)	2.040 -	2.150 *0.0004*	2.022 *0.0036*
Product design change[15]	Design for recycling	0.151 -	0.258 *0.0000*	0.198 *0.0000*
	Design for durability	0.121 -	0.199 *0.0000*	0.100 *0.0000*
	Design for recycling and durability	0.068 -	0.126 *0.0000*	0.072 *0.3071*
Environmental variables	Part of recycled inputs	0.424 -	0.409 *0.0000*	0.423 *0.9857*
	Waste streams	611.181 -	552.892 *0.0000*	608.344 *0.6368*
	Virgin materials flows	371.043 -	320.018 *0.0000*	365.615 *0.0635*
Recycler profit		111.089 -	42.249 *0.0000*	116.344 *0.4901*

Table 2. The effects of recyclability norms

[15] It returns the share of firms which have changed their product design. It is based on the firms which are still on the market.

The impact of norms on the development of recycler's activities and profits is critical since we can observe a significant decrease in profits in the case of the most stringent norms (Norm1). The higher level of concentration leads to larger profits for firms which will have a positive impact on product characteristics. Improvement in the level of recyclability of products tends to increase the supply of the recycler while the longer lifetime of products contributes to lessen input requirements of firms. This increase in supply combined with the decrease in demand leads to a drop in price and sales of recycled inputs and consequently to a drop in recycler's profits.

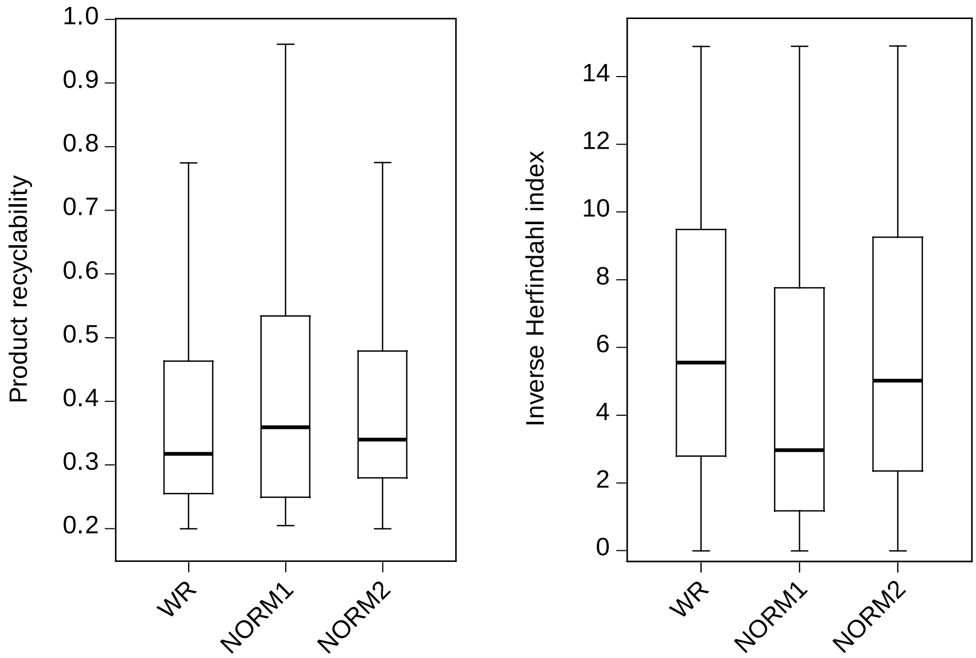

Fig.4. Distribution of product recyclability and inverse Herfindahl index

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). But at the same time, norms have a strong impact on market concentration. A trade-off must be found between preserving competition and static efficiency and encouraging radical change through selection mechanisms.

4. Conclusions

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 significant changes (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 involves a trade-off between the impact on concentration and the effects on innovation. 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.

This model calls for more research into the modelling of environmental policy instruments for waste prevention. We now plan to improve the basic model by investigating the effects of other EPR policy instruments upon industrial dynamics.

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Appendix

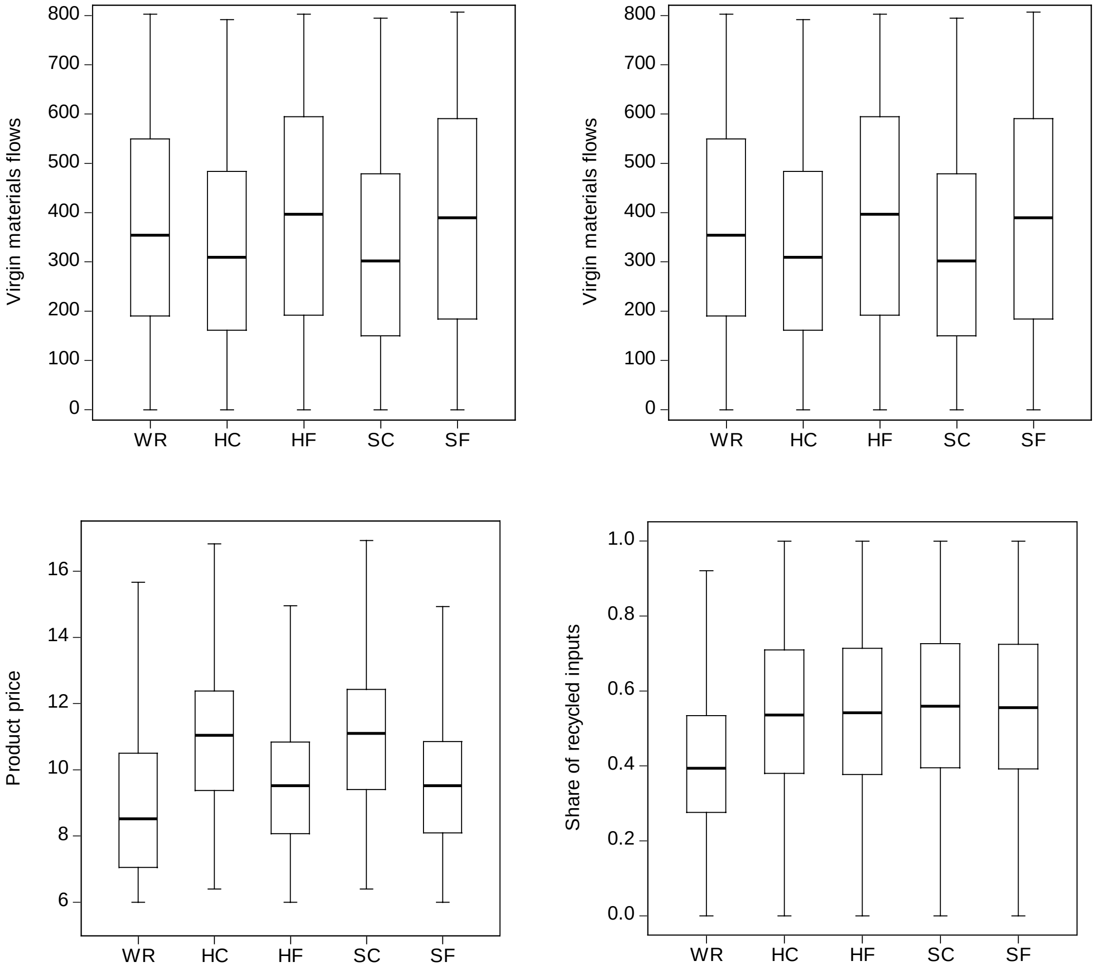

Fig.5. Simulation results (box-plots) in the case of recycling fees

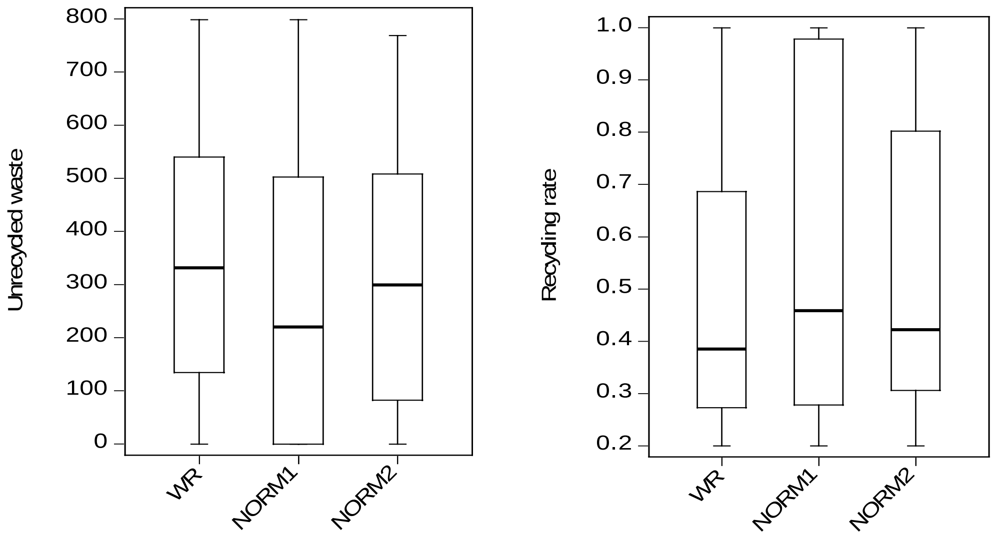

Fig.6. Simulation results (box-plots) in the case of recyclability norms