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**Innovation, sustainability and policy**

# Greening product design

## Modelling the impact of the recycling fee on industrial dynamics

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**Abstract.** This paper investigates the impact of a recycling fee on the dynamic of firms' environmental innovation strategies, waste management and on environmental variables. We address this issue by developing an evolutionary simulation model to describe the behaviour of business firms as interacting with that of consumers and recyclers. Our experiments show that the effect of the fee depends mainly on the design of the instrument and the way it is implemented. The model dynamics show that an individual fee, proportional to the recyclability of each product, paid by the consumers would be the most effective instrument.

***Key words:*** *Recycling – Product-life extension – Environmental innovation - Evolutionary modelling*

JEL Classification: O33, D21, Q53

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# 1. Introduction

Limiting continuous increase in waste volumes and protecting resources are becoming crucial environmental objectives in developed societies. For example, today in Europe, the emission of domestic waste per person per year is on average 550 kg. This statistic is far above the 330 kg objective of the Fifth European Community environment programme in 1993 (Council of the European Union, 1993). The Sixth Environment Action Programme objective is now "to ensure that the consumption of renewable and non-renewable resources does not exceed the carrying capacity of the environment and to achieve a decoupling of resource use from economic growth through significantly improved resource efficiency and the reduction of waste" (Commission of the European Communities, 2006). The present target is for waste to reduce quantity going to final disposal by 20% by the year 2010 and 50% by 2050.

When trying to prevent waste, one solution is to close the "material loop" (Stahel, 1983). A *linear industrial economy* (i.e. an economy where no loop exists) will lead to an accumulation of end of life products and an exhaustion of resources. One solution to the problem, therefore, is to build one or several loops making it possible to reintroduce into the production process, those products which have arrived back in post-consumption phase. Post-consumption recycling is the main solution. This means collecting waste, sorting it to recover materials which may be recycled, and then transforming these materials (physically and/or chemically) to obtain new raw materials.

Today, recycling plays an important role in waste management in many industry sectors, but the situation in the different recycling systems is extremely diverse. Some materials recycled for decades, such as glass, metal or paper for instance, already have an efficient recycling system and very high recyclability rates. At the same time, the recycling system of several end of life products, especially complex goods (waste of electric and electronic equipments, end of life vehicles, power units, etc), is still under construction and needs to be improved by developing not only design for recycling but also efficient management systems (Lacoste and Chalmin, 2006).

Improvement in product recyclability and recycling systems might well solve the problem of waste management but not the problem of waste growth (Cooper, 1994). Extending product life, by means of improvement in product reliability as well as by re-using products, maintenance, repair or reconditioning[2], could reduce waste streams (Stahel, 1994). But product life extension is much more complex to implement than design for recycling. In fact, design for recycling has the short-term advantage that it preserves the existing economic structures and is therefore easy to implement. Inversely, extending product lifetime implies significant changes both in product design and in the production process (Bellmann and Khare, 1999).

The other problem is that product-lifetime extension can lead to slowing down product replacement speed by consumers which will mean lowering sales over that period. For these reasons, firms in general are usually reluctant to adopt a lifetime extension strategy (King et al., 2004) and today, the tendency is rather to see a fall in product lifetime.

Developing loops involves change in product design. It involves integrated modifications of the core production process leading to a reduction of pollution at source (Saint Jean, 2005). Innovation strategies of firms are then crucial when trying to deal with the continuous increase in waste streams. They will determine the dynamic of the environmental characteristics of products and in turn the evolution of the environmental performance of the economy.

In order to encourage firms to change their innovation strategy, regulatory instruments can be introduced. In traditional Western legal systems, the production and consumption phase of a product's life cycle is more or less influenced by existing rules of responsibility and liability of the producer, thereby creating incentives for safe production. The post-consumer phase, on the other hand, traditionally has not been covered by responsibility of the producer. Extended Producer Responsibility (EPR) seeks to change this (Kroepelien, 2000). "EPR is an environmental protection strategy to reach an environmental objective of a decreased total environmental impact from a product, by making the manufacturer of the product responsible for the entire life-cycle of the product and especially for the take-back, recycling and final disposal of the product. The EPR is implemented through administrative, economic and informative instruments.

[2] Typical examples for these would include the re-treading of tyres, the Xerox life-cycle design programme for photocopiers, the Siemens-Albis AG portable operating system BS2000 aiming at designing goods for long life, using durable materials and replaceable components (Giarini and Stahel, 1989).

The composition of these instruments determines the precise form of the EPR." (Lindhqvist, 2000, p. 154). Regulations based on EPR have got a double objective: avoiding waste, by improving product design, and increasing the recycling of waste, by developing recycling process. In practice, EPR is implemented through recycling fee: firms or consumers have to pay for the recycling of their products.

The question will then be to study the effect of this fee on firms' strategic choices regarding the characteristics of their products while these firms are interacting with consumers and recyclers. How does it impact on R&D strategies of firms, waste management and environmental variables? To answer these questions, we present in this paper 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.

The paper is presented as follows. In the first section a description of the simulation model is presented. In the second section results of model experiments are discussed. The third section concludes.

## 2. 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 on the impact of a recycling fee on the development of green products. Our research will help to gain some understanding on issues related to the conditions and mechanisms with respect to change in firms' R&D strategies and the associated shift to green products production. 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 generalizations and understanding that we have looking at real data.

The structure of the model is based on the "History-friendly" model by Malerba et al. (1999, 2007). We have used the same kind of topography to characterize products and we modelled innovation and market dynamics in a similar way.

However, our model is not a “History-friendly” model: we do not aim to generate stylized facts to reproduce the dynamic of an industry.

Our model comes within the framework of Saint Jean (2005) and Janssen and Jagger (2002). Saint Jean studies the emergence and diffusion of clean technologies within interfirm vertical relationships and shows that attention needs to be given to evolutionary modelling of supply-demand chains and of technological complementarities (Van Den Bergh, 2007). Janssen and Jager investigate introduction and diffusion of green products by analysing relationships between firms and final consumers and by emphasizing social processing from the demand side. Our modelling experiment differs from these two works regarding several aspects and therefore, aims to provide new knowledge within the field of environmental innovation. In fact, our research question suggests focusing our approach on product environmental innovation and relationships between firms and final consumers. We introduce in the system the post-consumption phase in order to study explicitly the impact of firms' R&D choice on waste management and its consequences on ecological variables. We took into account in our demand-driven model three categories of actors: firms (*i*) all marketing a single generic finished product[3], end consumers buying those products, and recyclers recovering and recycling those end of life products used by consumers. These three categories of agents were made to interact at the various stages of the model.

## 2.1. Product’s characteristics

While Malerba et al. focus on technological performance and cheapness of any product, we focused our approach on its quality. The product *i* is characterized by its global quality divided into three dimensions: the technical quality of the product (*X*), its recyclability (*R*) and its lifetime (*LT*) (figure 1). These characteristics will develop and change according to firms' R&D strategy.

The technical characteristics of the product reflect its “conventional” quality. This is a multi-criterion dimension reflecting the performance of the technical attributes of the product during its use phase. *X* is a synthetic index which increases in proportion to the overall technical quality of the product. Each firm

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

will improve it to make its product more attractive towards consumers. *X* is limited by a fixed upper limit *Xmax* reflecting the maximal performance on this dimension.

*R* is the degree of recyclability of the product. A high degree of recyclability means that the product can be easily recycled, i.e. the product is made up of few different easily recyclable materials, few dangerous substances or products that can be easily dismantled etc[4]. We are presuming that there is an *Rmax1* recyclability threshold characterizing the design change needed to increase product recyclability. We considered that below this threshold, recyclability can be increased with the initial product design through specific technical and technological improvements. This means that *Rmax1* represents the maximum recyclability reachable through incremental innovations. Crossing this threshold will require 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* only by offering a new product based on a new design (design for recycling). *R* is limited by a fixed upper limit *Rmax2* with *Rmax1* < *Rmax2*.

*LT* reflects the product's durability. This is the number of periods over which the product is in working order and can be used by its owner. We are also presuming that there is an *LTmax1* lifetime threshold. This threshold characterizes the adoption of a new product design needed to extend the product's lifetime. The implementation of product life extension assumes the design of a radically new product: a product will need to be designed to be used over long time periods. This new product design must be backed up with a more severe quality control concerning the material and components choice and their assembly. Adopting policy for a product life extension strategy requires then radical innovations both in product design and in production structure. Below *LTmax1,* the product lifetime can be increased with the initial product design through incremental innovations. *LT* is limited by a fixed upper limit *LTmax2* with *LTmax1* < *LTmax2*.

[4] By *recycling,* we mean material reduction (i.e. reducing the amount of one or more materials needed to manufacture the product), material substitution (i.e. replacing one or more materials for ones that have less negative ecological effects) and material recycling (i.e. recycling a material which makes up the product) (Boons, 2002).

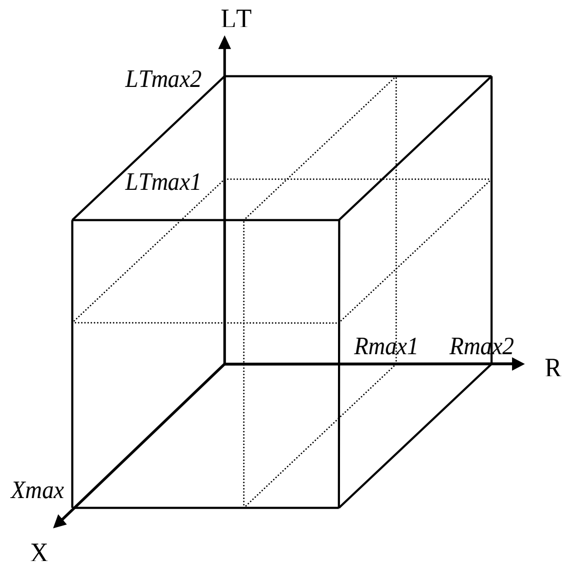


**Fig. 1.** Product's quality attributes

Positive or negative interactions between these three dimensions could emerge over the dynamic. In fact, a research activity may lead to design a new product more efficient on one or several dimensions, but less efficient on the other(s). However, these effects are not systematic and are not wanted by firms. They would create hazards in the model which would make the impact of innovation strategies on firms' performance more confused. Moreover, the objective of the firms is to progress on each quality dimension in order to obtain a competitive advantage. They will then retain only the best innovative solutions and will eliminate all those leading to a decrease in at least one of the three quality dimensions. Consequently, we suppose that the three quality dimensions of products are independent. We assume then, that the variation of the three quality attributes can only be positive and depends only on the firm's will to progress in this particular direction.

### 2.2. Supply - demand interactions

Each consumer uses one single product at the same time and renews its purchase when this product is at the end of its lifetime; i.e. when its lifespan *LT* expires; or when it becomes obsolete. In fact, the consumer can change its product when it is still in working order because the technical characteristics of this product do not satisfy its expectations any more. The obsolescence probabilities are based on a comparison of the technical quality *X* of the product currently used by the consumer with the best and the worst performance observed on the market in the current period (Silverberg and Verspagen, 1995). If the obsolescence draw is a success or if the product is at the end of its lifetime, the consumer sends it to the recycler and buys a new one. The consumer will then choose a new product according to product visibility (*V*):

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

This function is based on the utility function of Malerba et al. (1999). The visibility of the product is a specification of the total performance for the product. $\beta_1$, $\beta_2$ and $\beta_3$ are parameters. We assume that $\beta_1 + \beta_2 + \beta_3 = 1$. This function implies that visibility increases with the quality of the product and decreases with its selling price (*p*). The parameters $\beta_1$, $\beta_2$ and $\beta_3$ represent the consumer's preferences with respect to the product’s characteristics. *MS* is the market share of the firm and the parameter $\lambda$ reflects the bandwagon effect.

We introduced a degree of heterogeneity into the demand side. In an extension of Malerba et al.'s History-friendly model, Malerba et al. (2007) suppose that a certain section of consumers called "experimental users" have a strong preference for one product characteristic. In developed countries an increasing attention towards environmental issue can be observed making the responsible consumption a critical choice (Elkington, 1994; Peattie, 2001 ; Nyborg *et al.*, 2006). Such a choice is made by many individuals, but not by all of them. Bearing this in mind, we make the supposition that there are two types of consumers: "green" and "non-green". Green consumers pay greater attention to the environmental performance of the product while non-green consumers are more interested in its style. Consequently, $\beta_1$ for non-green consumers is higher than $\beta_3$, and inversely, $\beta_3$ for green consumers is higher than $\beta_1$[5].

As environmental characteristics are often difficult to observe and durability is difficult to estimate when buying a product, we assume that consumers cannot

[5] In addition, we assume that green consumers have lower obsolescence probabilities than non-green consumers because non-green consumers are supposed to be more demanding regarding its product's style and green consumers are supposed to have an aversion to throw away a product which is still in working order.

know perfectly the objective value of products' recyclability and lifetime. $\tilde{LT}_{i,t}$ is then drawn from a normal distribution $N(LT_{i,t}, \sigma_{LT})$ and $\tilde{R}_{i,t}$ is drawn from a normal distribution $N(R_{i,t}, \sigma_R)$ (Saint Jean, 2005).

We suppose that the consumer's behaviour is a bounded rational one (Simon, 1982). The consumer cannot take an optimal decision consisting in choosing the product with the best visibility. The rule to choose a product is then random with probabilities proportional to products' visibility.

To take into account each person's budgetary constraints, any consumer will tend to be characterized by an individual maximum price. The selling price of the selected product cannot exceed that price. If no product on the market meets this requirement, the consumer will not buy any product over that period. This means that he will then own no product and have to be excluded from the market until at least one product reaches a price lower than its maximum price.

### 2.3. Firms' R&D investment

Each firm invests for each period in R&D a fixed proportion ($\mu$) of its profits ($\Pi$) for the previous period[6]. R&D investment seeks to improve the quality of any product and, consequently, its visibility (*see* 2.2). Such a rise in product visibility will give the firm an opportunity to increase its market share. Innovation is then the only way to improve economic performance. *RD* is divided into expenditure aiming at increasing the product's technical quality ($RD^X$), its lifetime ($RD^{LT}$) and its recyclability ($RD^R$):

$$RD_{i,t}^{X} = \delta_{i,t}^{X}.RD_{i,t} \quad (2.a)$$

$$RD_{i,t}^{LT} = \delta_{i,t}^{LT}.RD_{i,t} \quad (2.b)$$

$$RD_{i,t}^{R} = \delta_{i,t}^{R}.RD_{i,t} \quad (2.c)$$

The firm specific variables $\delta$ reflect the firm's distribution choice of R&D expenditure and consequently its innovation strategy regarding its product's characteristics.

[6] $\mu$ is a firm specific parameter.

## 2.4. The innovation process

The successive R&D investments allow accumulating knowledge about each of the three quality dimensions. This accumulated knowledge ($S$) will be used by the firm to innovate. In fact, knowledge level determines the probabilities of access to new values within the range of product characteristics (Silverberg and Verspagen, 1995). Access probabilities to a new technical performance ($Prob^X$) are logistic functions of the knowledge level reached in terms of technical quality ($S^X$). The same applies to the two dimensions $LT$ and $R$ using the knowledge level reached in terms of product lifetime ($S^{LT}$) and recyclability ($S^R$).

The innovation process means increasing the value of at least one of the three product's characteristics according to functions specified hereafter.

If the innovation draw for $X$ is a success, the improvement of the value of this characteristic is given by:

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

This equation implies that the value of the increase in $X$ depends on the knowledge level reached in terms of technical quality, the distance of the achieved design to the frontier and the cumulated experience ($E$)[7]. The parameter $\alpha_X$ is a scale parameter. Parameters $\gamma_1$, $\gamma_2$ and $\gamma_3$ are selected so that their sum is equal to 1. These parameters respectively reflect the impact of the knowledge level, the impact of the exhausting of innovation opportunities and the impact of experience on the extent of improvement to the considered characteristic.

In a same way, if the innovation draw for $LT$ is a success, the improvement of the value of this characteristic is given by:

$$\Delta LT_{i,t} = \alpha_{LT} . \left(S_{i,t}^{LT}\right)^{\gamma_1} \left(\mathrm{LTmax} - LT_{i,t-1}\right)^{\gamma_2} . (E_{i,t})^{\gamma_3} \quad (3.b)$$

[7] The variable $E$ reflects the number of periods spent in a particular potential. In fact, the time spent in a potential leads the firm to accumulate experience giving it better opportunities to increase the performance of its product.

with *LTmax* = *LTmax1* if $LT_{i,t-1} \leq$ *LTmax1* and *LTmax* = *LTmax2* if $LT_{i,t-1}$ > *LTmax1*.

The boundary of the initial product design *LTmax1* can be reached through incremental innovation. Equation (3.b) reflects that incremental change will be faster when distance to *LTmax1* is larger. Crossing this boundary requires radical innovation, but it is less likely because innovation steps become smaller when approaching *LTmax1*. Accordingly, changing product design will require a high knowledge level $S^{LT}$, and so a considerable R&D investment $RD^{LT}$ in order to implement the major changes needed in the production process.

If the innovation draw for *R* is a success, the improvement of the value of this characteristic is given by:

$$\Delta R_{i,t} = \alpha_R . \left(S_{i,t}^R\right)^{\gamma_1} \left(\mathrm{Rmax} - R_{i,t-1}\right)^{\gamma_2} . (E_{i,t})^{\gamma_3} \qquad (3.c)$$

with *Rmax* = *Rmax1* if $R_{i,t-1} \leq$ *Rmax1* and *Rmax* = *Rmax2* if $R_{i,t-1}$ > *Rmax1*.

On the other hand, if the innovation draw is a failure, performance remains unchanged[8].

The experience *E* will decrease at several critical moments of the dynamic. In fact, when a firm adopts a new product design (i.e. when the firm crosses the threshold *LTmax1* and/or *Rmax1*) a part or the totality of its cumulated experience disappears. In order to develop a product design with a high lifetime and/or recyclability potential, the firm has to revise the conception process of its products. This implies radical changes within the production process leading to major organisational mutations and a radical renewal of the required knowledge and capabilities. Accumulated experience in a particular product design can become therefore useless to develop the new product.

## 2.5. The production process

The manufacture of products requires a certain quantity of inputs. We suppose that there are two categories of perfectly substitutable inputs: recycled inputs and virgin inputs. Recycled inputs are provided by the recycler, the virgin inputs by

[8] Parameters $\gamma_1$, $\gamma_2$ and $\gamma_3$ are the same in the equations (3.a), (3.b) and (3.c).

suppliers external to the model. The share of recycled inputs constituting the product reflects the firm's preference towards recycled materials and consequently its demand. It depends on the quality of these materials and the difference between their price and the price of the virgin materials.

We determine then the product unit cost of production (*CM*) to fix its selling price. The selling price of the product is defined as a minimum price (*pmin*) to which the firm adds a fixed mark-up. This minimum price is based on the product unit cost of production from the previous period. Two cases arise.

If $LT_{i,t} \leq LTmax1$, the firm markets a product with a short lifetime design. In this case *pmin* is equal exactly to the unit cost of production of the previous period:

$$p\min_{i,t} = CM_{i,t-1} \qquad (4.a)$$

If $LT_{i,t} > LTmax1$, the product is designed to have a long lifetime design. In this case an extra cost (*AddC*) appears in the production process and so *pmin* is higher:

$$p\min_{i,t} = CM_{i,t-1}.\left(1 + AddC_{i,t}\right) \qquad (4.b)$$

This extra cost reflects the additional expenditure related to the more rigorous quality control the firm has to implement concerning the selection of its materials and product components and their assembly to extend significantly its product lifetime (*see* 2.1). Products with a long lifetime design are then more expensive to produce and consequently, they are more expensive than those with a shorter lifetime (Janssen and Jager, 2002). However, by training and through accumulated experience, the firm will be able to lower *AddC*. In fact, once the firm crosses the *LTmax1* threshold and markets a product with a long lifetime design, its R&D investment allocated to *LT* ($RD^{LT}$) will not only contribute to increasing the lifespan of that product (exploiting the potential offered by the new design) but will also lower the extra cost. For each period, there will be two innovation draws for *LT*: the first to know if *LT* has increased, the second to know if *AddC* has decreased. Accordingly, one R&D investment can contribute to improvements in both product lifetime and in extra cost. The first draw has been presented previously (*see* 2.4). Regarding the second draw, if it is a success, the fall in the value of the extra cost will be given by:

$$\Delta AddC_{i,t} = \alpha_{AddC} . \left(S^{LT}_{i,t}\right)^{\gamma_1} \left(AddC_{i,t-1}\right)^{\gamma_2} . (E_{i,t})^{\gamma_3} \qquad (5)$$

$\alpha_{AddC}$ is a scale parameter and the parameters $\gamma_1$, $\gamma_2$ and $\gamma_3$ are the same than those used in the equations (3.a), (3.b) and (3.c).

Starting from the selling price, the number of products sold in the current period and the minimum price we can fix the gross profits ($\Pi$) for each firm.

### 2.6. The transition dynamics

Adopting a new product design needs time and money. Changing design requires a transition period over which the firm will face additional costs (Malerba et al, 1999). As soon as a new product design is adopted[9], the firm enters in an adoption phase over which an adoption cost will have to be borne. This adoption cost is a fixed cost equal to $AC^{LT}$ when the firm crosses the threshold *LTmax1* and adopts a long lifetime product design and $AC^{R}$ when the firm crosses the threshold *Rmax1* and adopts a design for recycling. These costs will be borne by the firm over several periods following the adoption[10] and consequently, will lower the firm's profits. The net profits are then equal to the gross profits minus the 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.

### 2.7. Firm strategy for innovation

Firms' R&D strategies may change over time in order to fit their behaviour to the fluctuations of their environment. Firms' strategies for innovation 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

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

[10] $AC^{LT}$, $AC^{R}$ and the duration of payment are identical for all the firms.

two times. The first time determines if the firm wants to change its R&D strategy. The second time fixes the new strategy.

Only firms with unsatisfactory profit levels will choose to change their strategy. This assumption reflects the satisficing behaviour of the firm linked to the context of bounded rationality. The firm will decide then to change its R&D strategy with probabilities proportional to its gross profits and the best and the worst profits observed on the market in the current period (*Πmax* and *Πmin*):

$$\Pr ob_{i,t}^{Change} = k.\left(1 - \frac{\Pi_{i,t} - \Pi \min_t}{\Pi \max_t - \Pi \min_t}\right) \quad (6)$$

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 copying the value of the variables $\delta^X$, $\delta^{LT}$ and $\delta^R$.

The second solution 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 $\delta^X$, $\delta^{LT}$ and $\delta^R$ within the admissible range [0,1]. The new R&D strategy of the firm is then given by:

$$\delta_{i,t}^{X} = \min\left[1, \max\left(\delta_{i,t-1}^{X} + \Delta\delta_{i,t}^{X}, 0\right)\right] \quad (7.a)$$

$$\delta_{i,t}^{LT} = \min\left[1, \max\left(\delta_{i,t-1}^{LT} + \Delta\delta_{i,t}^{LT}, 0\right)\right] \quad (7.b)$$

$$\delta_{i,t}^{R} = \min\left[1, \max\left(\delta_{i,t-1}^{R} + \Delta\delta_{i,t}^{R}, 0\right)\right] \quad (7.c)$$

with

$\Delta\delta_{i,t}^{X} \sim N(0, \sigma)$

$\Delta\delta_{i,t}^{LT} \sim N(0, \sigma)$

$\Delta\delta_{i,t}^{R} \sim N(0, \sigma)$

and with $\delta^X + \delta^{LT} + \delta^R = 1$.

The firm will randomly choose between imitation and mutation with probabilities proportional to its imitation propensity.

### 2.8. The recycler

The recycler is the main actor within the post-consumption phase. To simplify, we are supposing 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 and sells to the firms as recycled inputs. The recycler does not recycle every part of the end of life product, but only that part which can be recycled which, in turn, will depend on the recyclability (*R*) of that product[11]. Consequently, the sum of the recyclabilities (*R*) of the various end of life products determines the recycled inputs supply created by the recycler over the period[12]. Then this supply, created over the current period, adds to the exiting stock of recycled inputs to give the total recycled inputs supply.

Comparison between supply and demand for recycled inputs from the previous period gives the price of these inputs in the current period.

The recycler invests, then, for each period in R&D a fixed proportion of its profits for the previous period to increase the quality of its recycled materials and to lower its marginal production cost[13].

The R&D investment and the innovation process of the recycler and firms are modelled according to the same principles and the same kind of formalization (*see* 2.3 *and* 2.4). The R&D investment of the recycler is then divided into expenditure aiming at increasing the quality of its materials and lowering its production cost. These successive R&D investments allow accumulating knowledge about materials quality and production efficiency. This knowledge is used to innovate by determining the probabilities of access to a new materials quality and production cost. When the innovation draws are a success, the value of the recycled inputs quality and/or their production cost will improve following preset trajectories based on decreasing outputs.

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[11] Thus, starting from a unit of product, the recycler manufactures and sells *R* units of recycled inputs.

[12] We are assuming that the part which cannot be recycled is incinerated or stocked in a waste disposal site.

[13] We have to notice that production cost of the recycler is characterized by large fixed costs because recycling activities requires a large capital stock (machines, infrastructure…).

The improvement of the recycled materials quality will increase the demand for this type of inputs, i.e. the share of recycled inputs constituting the product will increase for all the firms on the market. The improvement of the production efficiency of the recycling process will lead to lower the marginal production cost of the recycler and then it will increase its profits.

## 2.9. The recycling fee

Each sale, we assume that firms pay the recycler for the recycling of their products. Concerning the calculation of the recycling fee (*f*), we will study two cases. In the first case, we model a single fee identical for all the firms. The fee is proportional to the average recyclability of the products on the market:

$$f_{i,t} = l.\left(\frac{R\max\ 2}{\overline{R}_t}\right) \quad (8.a)$$

with

$$\overline{R}_t = \frac{\sum_{i=1}^{n_t} R_{i,t}.Q_{i,t}}{\sum_{i=1}^{n_t} Q_{i,t}}$$

In the second case, the fee is individual, proportional to the recyclability of the product sold by the firm:

$$f_{i,t} = l.\left(\frac{R\max\ 2}{R_{i,t}}\right) \quad (8.b)$$

The parameter *l* represents the minimal level of the fee.

As this fee is an additional cost for the firm, it reduces its gross profit. In order to prevent this drop, the authorities could permit firms to integrate the recycling fee in the selling price. In this case, consumers will pay for the recycling of their product.

In the final analysis, we will study four types of design for the instrument:

- A single recycling fee paid by the consumers. We will call this case UC.
- A single recycling fee paid by the firms. We will call this case UF.
- An individual recycling fee paid by the consumers. We will call this case IC.
- An individual recycling fee paid by the firms. We will call this case IF.

These cases will be compared with of case without regulation (*SR*).

The recycling fee is an additional financial resource for the recycler. His profit will then increase by $\sum_{i=1}^{n_t} f_{i,t}.Q_{i,t}$ , with $Q$ reflecting the quantity of products sold by each firm.

The model defined in this manner enables, by means of simulations, a study of the impact of the recycling fee on the evolution of firms' innovation strategies and changing trends in waste production and recovery. Figure 2 summarizes the model structure.

# 3. Simulation results

## 3.1. Experimental set-up

We used the LSD 5.6 simulation platform[14] to compute and run the model. In the simulation experiments, we formalised 1 000 consumers and 1 recycler. The number of firms initially on the market is randomly chosen between 5 and 15. In this model no entries of firms and consumers are assumed. A Monte-Carlo method was adopted. We ran 10 000 simulations where the number of periods was randomly chosen between 250 and 500. The results of the last period of each simulation were studied. The simulations were initialized with a randomly drawn vector of values for the main parameters of the model. As a result, we obtained a set of 10 000 observations covering quite a diversified subset of the parameter

[14] http://www.business.aau.dk/~mv/Lsd/lsd.html

space. To analyse the simulations results we used box plots and Wilcoxon-Mann-Whitney tests[15].

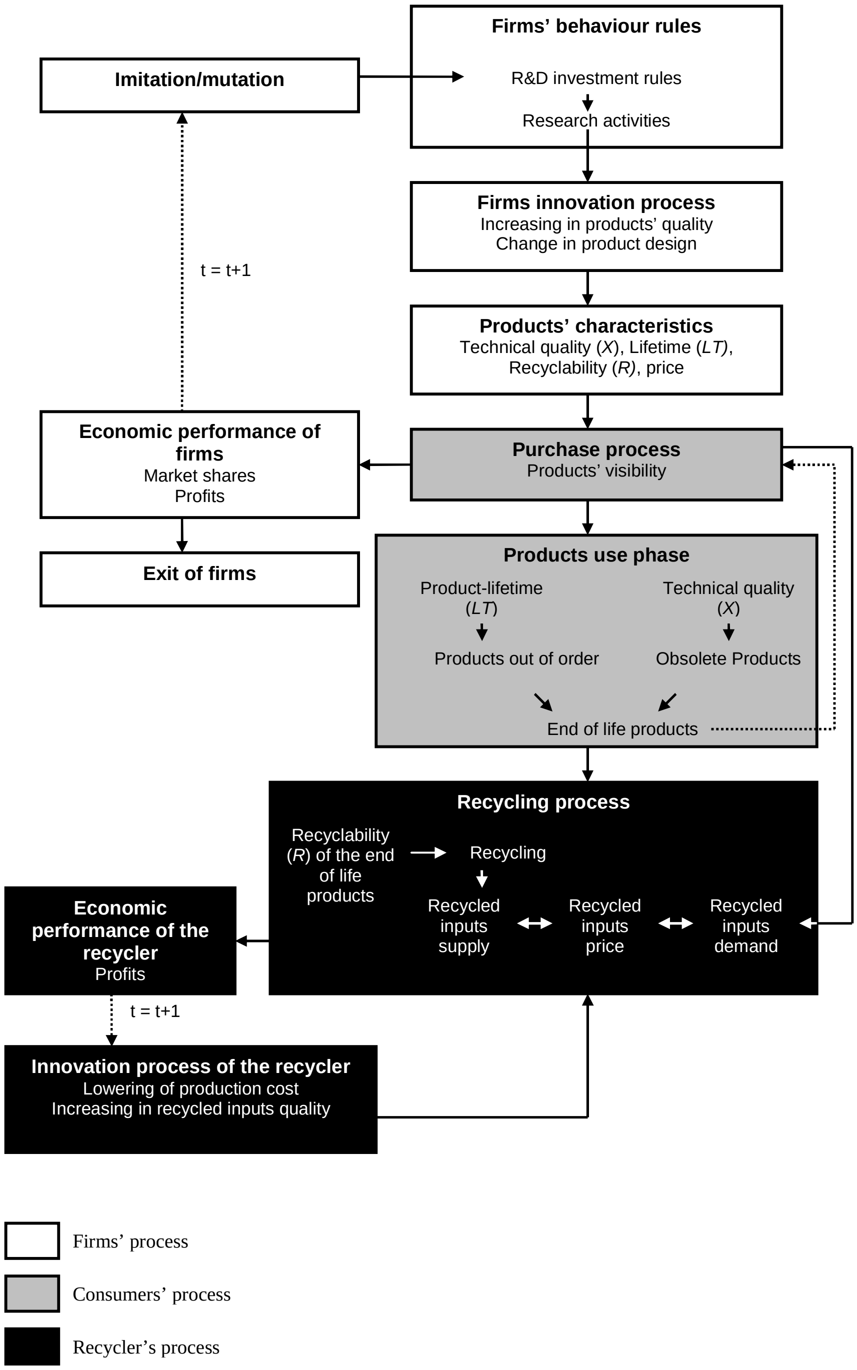



**Fig. 2.** Model structure

[15] We used Eviews 5 and R to analyse the simulations results. Interested readers may obtain a full copy of the detailed initialization of the parameters and variables of the model and the results of the Wilcoxon-Mann-Whitney tests by writing to the author.

## 3.2. Impact of the recycling fee on the innovation strategies

Change in R&D strategies only occurs in the cases IC and IF. The box plots of the figure 3.a and Wilcoxon-Mann-Whitney tests show no significant difference between the cases SR, UC and UF.

**Proposition 1:** *only an individual recycling fee would encourage firms to change their R&D strategy. A single fee, identical for all the firms, is not an incentive instrument.*

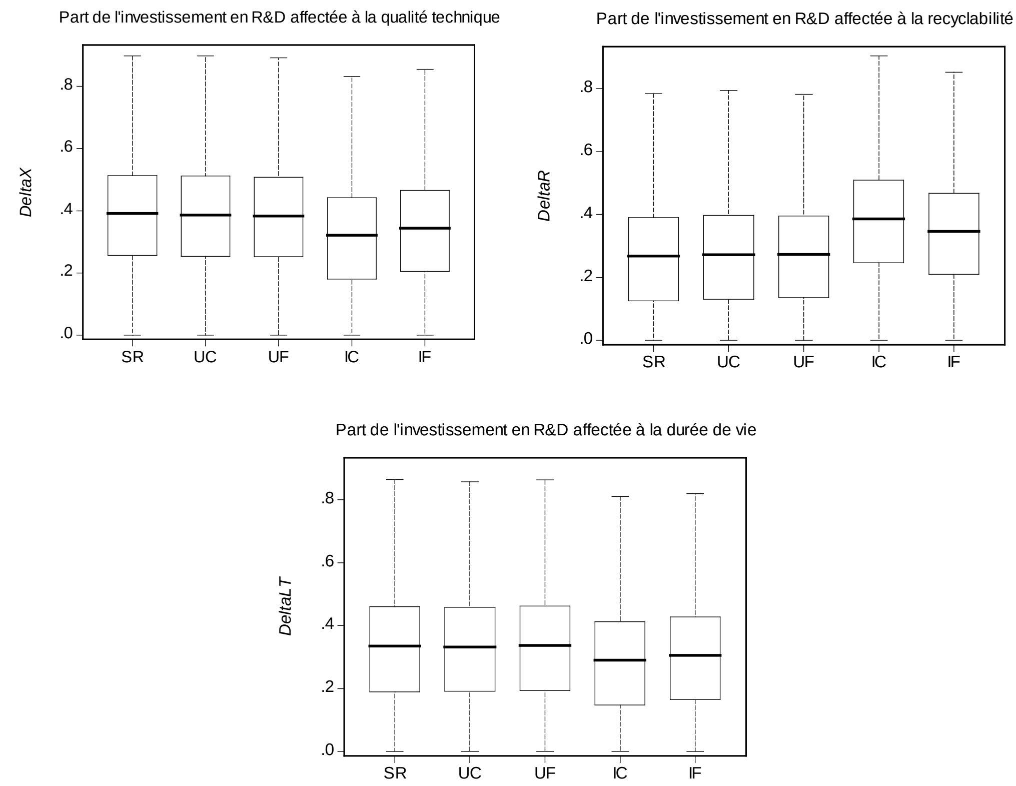
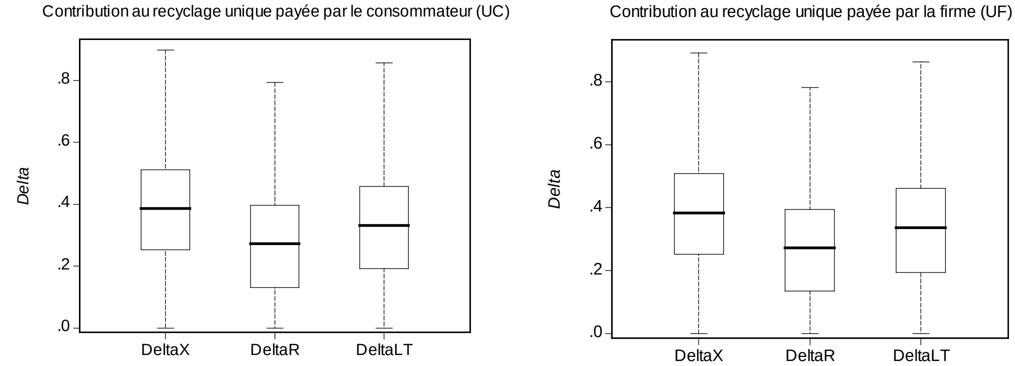



**Fig. 3.a.** Firms R&D strategy



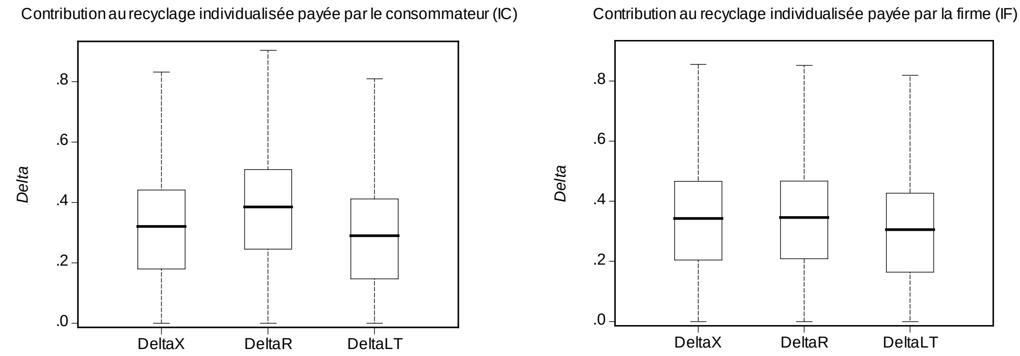



**Fig. 3.b.** Firms R&D strategy

In the cases UC and UF, the extra cost for highly recyclable products is the same than the extra cost for the least recyclable products. Consequently, the best firms will not be rewarded by the regulation and the worst firms will not be encouraged to change their R&D strategy in order to increase the recyclability of their product.

On the contrary, in the cases IC and IF, the lower the product recyclability is, the higher the fee will be. In the case IC, the worst firms will be penalized by higher selling prices and in the case IF, they will make lower profits. In these two cases, the economic performance of these firms will be lower because of the recycling fee and it would encourage them to change their behaviour. Then, they will tend to copy the strategies of the best firms, those producing a highly recyclable product. The part of the profits aiming at increasing the product's recyclability ($\delta^R$) will rise in the cases IC and IF, while the parts aiming at increasing technical quality ($\delta^X$) and lifetime ($\delta^{LT}$) will decrease (figure 3.a).

A single fee identical for all the firms is not an incentive instrument. Only an individual recycling fee would encourage firms to change their R&D strategy. The problem is that, in practice, this type of fee is very difficult to implement because it needs a lot of information: the authorities have to know the recycling rate of each product.

## 3.3. Impact of the recycling fee on the technological dynamic

Change in R&D strategies contributes to improve environmental performance only in the case IC. In the case IF, the fee leads to lower profits (figure 4).

Consequently, even if the part of the profits aiming at increasing the product's recyclability is higher, the R&D investment decreases.

In the case IC, the fee leads to a rise in prices, which prevent some consumers to buy a product because their individual maximum price is too low. The sales of the firms decrease and consequently their profits are lower. Nevertheless, this fall is small and as the part of the profits invested the product's recyclability is higher, the expenditure aiming at increasing recyclability rise. Finally, products recyclability is higher in the case IC and lower in the case IF (figure 5)[16].

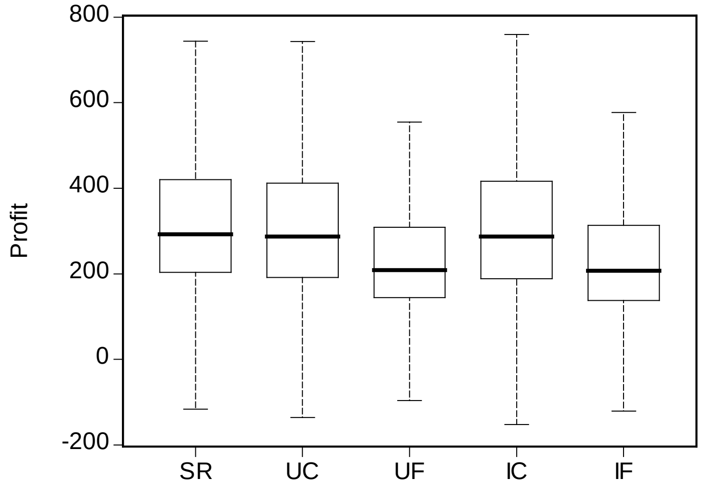



**Fig. 4.** Firm's profits

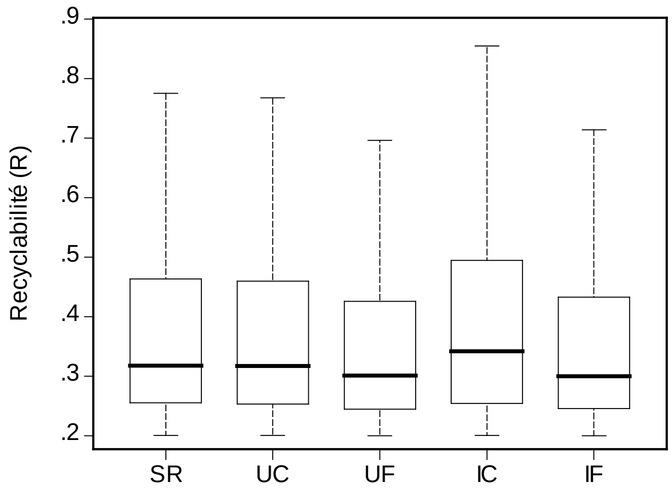



**Fig. 5.** Product recyclability

[16] For the same reasons, the recycling fee leads to lower profits in the cases UC and UF. But, contrary to the cases IC and IF, $\delta^R$ is not higher. Consequently, the fall in R&D investment is greater. Nevertheless, the differences between all the cases are small.

**Proposition 2:** *only an individual recycling fee paid by consumers would improve products recyclability. When the fee is paid by firms, we obtain a lower recyclability. Nevertheless, the extent of these effects remains small.*

The lower profits have a negative impact on the other dimensions $X$ and $LT$ (tables 1 and 2) and it makes harder change of product design. The table 3 shows that when a fee is introduced, the share of firms changing their product design is identical or lower than the share observed in the case without regulation. The share increases only in the case IC because of the higher products recyclability, but the difference with the case SR is small.

| Wilcoxon-Mann-Whitney tests | | |
|---|---|---|
| **Category statistics** | **Value** | **Probability** |
| ***SR-UC*** | *0.996356* | *0.3191* |
| ***SR-UF*** | *12.52511* | *0.0000* |
| ***SR-IC*** | *2.517937* | *0.0118* |
| ***SR-IF*** | *14.59095* | *0.0000* |

**Tab. 1.** Wilcoxon-Mann-Whitney tests of the technical quality of the product ($X$)

| Wilcoxon-Mann-Whitney tests | | |
|---|---|---|
| **Category statistics** | **Value** | **Probability** |
| ***SR-UC*** | *2.570906* | *0.0101* |
| ***SR-UF*** | *13.11708* | *0.0000* |
| ***SR-IC*** | *4.061995* | *0.0000* |
| ***SR-IF*** | *14.66938* | *0.0000* |

**Tab. 2.** Wilcoxon-Mann-Whitney tests of the product-lifetime ($LT$)

| Case | Design for recycling | Design for durability | Design for recycling and durability |
|---|---|---|---|
| SR | *0.212* | *0.199* | *0.085* |
| UC | *0.205* | *0.199* | *0.084* |
| UF | *0.188* | *0.168* | *0.072* |
| IC | *0.221* | *0.195* | *0.089* |
| IF | *0.197* | *0.165* | *0.074* |

**Tab. 3.** Share of firms changing its product design

**Proposition 3:** *a recycling fee cannot encourage firms to change radically their product design.*

These results are in line with the proposition of Kemp and Pontoglio (2008) that the capacity of economic instruments to favour radical technological change is empirically limited. They would be more effective in stimulating incremental change and technology diffusion.

The recycling fee will impact the market structure. A recycling fee paid by consumers tends to increase the market concentration while a recycling fee paid by firms would lower it (table 4)[17]. In the case IC, the concentration is high because the firms with the best product recyclability are favoured by the regulation and increase their market share to the detriment of the firms with low product recyclability. The gap in terms of market share is then higher, which increases the market concentration.

On the contrary, in the cases UF and IF, the smaller innovation opportunities (due to the lower profits) reduce the gap in terms of market share, which lowers the market concentration. In the case UC, the fee has no impact on the market concentration because it has no impact on economic and environmental performance of firms.

| Wilcoxon-Mann-Whitney tests | | |
|---|---|---|
| **Category statistics** | **Value** | **Probability** |
| ***SR-UC*** | *0.693988* | *0.4877* |
| ***SR-UF*** | *7.373499* | *0.0000* |
| ***SR-IC*** | *2.630904* | *0.0085* |
| ***SR-IF*** | *5.775253* | *0.0000* |

**Tab. 4.** Wilcoxon-Mann-Whitney tests of the market concentration

[17] The tableau 4 shows that the difference between the cases SR and IC, SR and IF and SR and UF are significant. The difference between the cases SR and UC is not significant.
met en évidence une différence significative entre les cas SR et IC, SR et IF, ainsi que SR et UF. En revanche la différence entre les cas SR et UC n’est pas significative.

### 3.4. Impact of the recycling fee on the recycler

A major objective of the recycling fee is to bring a financial support to the recycler. The simulations show that the fee leads to a great rise in recycler's profits (figure 6).

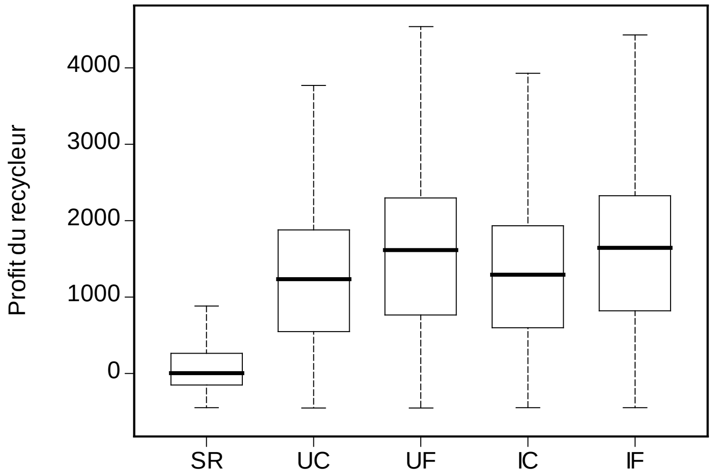



**Fig. 6.** Recycler's profits

**Proposition 4:** *whatever the design of the instrument, the recycling fee reduces the financial constraint of the recycler. The fee ensures the continued existence of the recycling activity and allows its development.*

The larger profits allow a greater investment in R&D, which leads to major progress in terms of process productivity and material quality. The better productivity leads to lower production costs and strengthens the profitability of the recycling activity. The better material quality encourages firms to choose the recycled inputs instead of the virgin materials (figure 7).

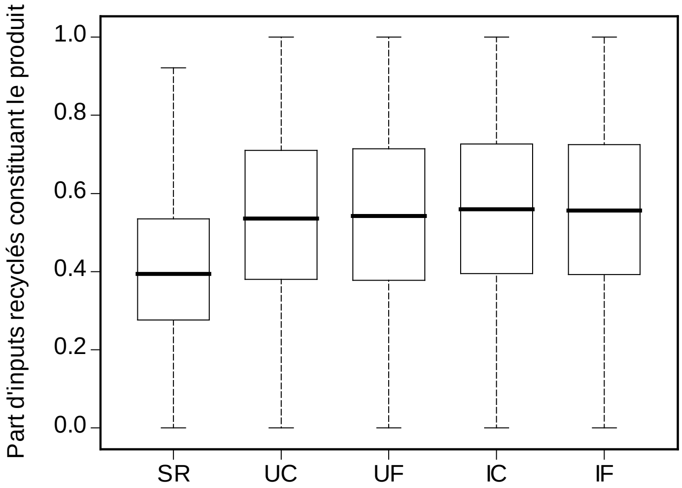



**Fig. 7.** Share of recycled inputs constituting the product

### 3.5. Effectiveness of the recycling fee

Concerning the two major objectives of the EPR; i.e. encouraging firms to change their innovation strategy and financing the recycling activity; simulations show that:

- The two objectives are reached only with an individual fee, proportional to the recyclability of each product. In fact, the four types of design for the instrument lead to the development of the recycling process and allow new technological trajectories for the recycler, but only an individual fee has an incentive effect on firms;
- Only an individual fee paid by the consumers leads to a better environmental quality of the products. When the fee is paid by the firms, the lowers profits offset the change in the direction of the R&D strategies towards product recyclability. A simultaneous rise in the global R&D expenditure; i.e. a higher value for $\mu$ (*see* 2.3); would compensate for the lower available financial resources. In this way, an additional policy aiming to support the research expenditure of the firms through incentive mechanisms or direct financial supports seems essential with this type of design of the instrument.

These results are in line with the empirical conclusions of Røine and Lee (2006), Gottberg *et al.* (2006), Gerrard and Kandlikar (2007) and Mayers (2007) showing that the regulations based on EPR have a positive effect on the recycling activity and the innovation process of the post-consumer phase, but they have at the same time a limited or no impact on the product characteristics. As these empirical studies, our model shows that a fee identical for all the firms paid by the consumers (UC) does not lead to a better environmental quality of the products and does not encourage change in product design (Clift and France, 2006).

Concerning the environmental impact of the fee, our experiments show that:

- The effects of the recycling fee on the global environmental variables are limited. The environmental quality of the products is not much affected by the regulation;
- A recycling fee paid by the firms appears harmful because it leads to an environmental performance lower than the one obtained without regulation (lower recycling rate, higher waste flows);
- From an environmental point of view, a recycling fee paid by the consumers seems desirable because it leads to lower waste flows and a lower pressure on virgin resources. In the case of an individual fee, the instrument leads to a better recycling rate too.

# 4. Conclusions

We developed an agent-based model to investigate the impact of a recycling fee on the environmental innovation strategies of the firms and on waste management and environmental variables.

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 effect of the regulation on the dynamic of the system.

First, our results provide us with insights about policy implications. The simulations show that the environmental and technological dynamics depends on the design of the fee. In fact, the results obtained depend mainly on the way the recycling fee is formulated and applied. Our experiments confirm the proposition of Kemp and Pontoglio (2008) that policy instruments are complex ‘things” and the effects of any policy are linked to the design of the instrument and the context in which they are applied. Technology responses are not a simple response to regulatory pressure and the impacts of policy instruments depend on how the instrument is formulated and used.

The model dynamics show that an individual fee paid by the consumers would be the most effective instrument because it fulfils the objectives of the EPR and it leads to a better environmental performance. Only this type of fee would lead to a win-win effect (Porter and Van der Linde, 1995) through the better market share of the firms with the highest product recyclability and the better level reached on this environmental dimension. Nevertheless, the fee leads at the same time to a rise in products’ price and lower technical quality and product-lifetime. Consequently, consumers would have a negative point of view towards this type of regulation: they would see the fee as an additional tax. Moreover, this type of fee would lead to lower profits for the firms. Concerning the better environmental performance provided by the fee, we have to notice that the regulation does not lead to a radical change in product design and the environmental progress is not linked to an eventual better environmental quality of the products. In fact, we can observe lower waste flows and a lower pressure on virgin resources because the fee leads to a rise in products’ price which excludes some consumers from the market[18]. The demand is lower and the number of sales decreases. Consequently, there are fewer quantities of waste to manage and firms need fewer quantities of inputs.

Finally, implementing an individual recycling fee, proportional to the recyclability of each product is very difficult because the authorities have to know exactly the objective recyclability of all the products of the economy. Nevertheless, an intermediate situation between the two extreme cases studied (a single fee and an individual fee) could be considered, for example by calculating different fees for different groups of products listed on the base of their environmental performance.

[18] The consumers excluded from the market are those with a maximum price too low to buy a product.

This model calls for more research into the modelling of the development and diffusion of green products. We now plan to improve the basic model by adding other policy measures based on EPR in order to be able to study their impact on the market dynamic.

# References


Bellmann, K., Khare, A., 1999. Economic issues in recycling end-of-life vehicles. Technovation 20, 677-690.

Boons, F., 2002. Greening products: a framework for product chain management. Journal of Cleaner Production 10, 495-505.

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

Commission of the European Communities, 2006. Communication from the Commission to the Council, the European Parliament, the Economic and Social Committee and the Committee of the Regions of 24 January 2001 on the Sixth Environment Action Programme of the European Community "Environment 2010: Our future, our choice". COM(2001) 31 Final - Not published in the Official Journal, Brussels.

Cooper, T., 1994. Beyond Recycling: The Longer Life Option. New Economics Foundation, London.

Council of the European Union, 1993. Resolution of the Council and the Representatives of the Governments of the Member States, meeting within the Council of 1 February 1993 on a Community programme of policy and action in relation to the environment and sustainable development, Official Journal C 138, 17.05.1993.

Elkington J., 1994, Towards the Sustainable Corporation: Win Win Win Business Strategies for Sustainable Development. *California Management Review* 36 (2), pp.90-100

Gerrard J., Kandlikar M., 2007, Is European end-of-life vehicle legislation living up to expectations? Assessing the impact of the ELV Directive on 'green' innovation and vehicle recovery. *Journal of Cleaner Production* 15 (1), pp. 17-27

Giarini, O., Stahel, W., 1989. The Limits to Certainty: Facing Risks in the New Service Economy. Boston, Mass. Kluwer Academic Publishers.

Gottberg A., Morris J., Pollard S., Mark-Herbert C., Cook M., 2006, Producer responsibility, waste minimisation and the WEEE Directive: Case studies in eco-design from the European lighting sector. *Science of The Total Environment* 359 (1-3), pp. 38-56

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

Kemp, R., Olsthoorn, X., Oosterhuis, F., Verbruggen, H., 1992. Supply and Demand Factors of Cleaner Technologies: some empirical evidence. Environment and Resource economics 2, 615-634.

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

King, A., Ijomah, W.L., McMahon, C.A., 2004. Reducing Waste: Repair, Recondition, Remanufacture or Recycle? Sustainable Development Journal.

Kroepelien K.F., 2000, Extended Producer Responsibility - New Legal Structures for Improved Ecological Self-Organization in Europe? *Review of European Community and International Environmental Law* 9 (2), pp. 165-177

Lacoste, E., Chalmin, P., 2006. Du rare à l'infini: panorama mondial des déchets 2006. Economica, Paris.

Lindhqvist, T., 2000. Extended Producer Responsibility in Cleaner Production : Policy Principle to Promote Environmental Improvements of Product Systems. IIIEE, Lund University.

Malerba, F., Nelson, R., Orsenigo, L., Winter, S., 1999. « History-friendly » models of industry evolution: the computer industry. Industrial and Corporate Change 8 (1), 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, 371-399.

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

Nyborg K., Howarth R.B., Brekke K.A., 2006, Green consumers and public policy: On socially contingent moral motivation. *Resource and Energy Economics* 28 (4), pp.351-366

Peattie K., 2001, Golden goose or wild goose? The hunt for the green consumer. *Business Strategy and the Environment* 10 (4), pp. 187-199

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

Røine K., Lee C.Y., 2006, With a Little Help from EPR? Technological Change and Innovation in the Norwegian Plastic Packaging and Electronics Sectors. *Journal of Industrial Ecology* 10 (1-2), pp. 217-237

Saint Jean, M., 2005. Coevolution of suppliers and users through an evolutionary modelling. The case of environmental innovations. European Journal of Economic and Social Systems 18 (2), 255-284.

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

Simon, H.A., 1982. Models of Bounded Rationality. MIT Press, Cambridge.

Stahel, W., 1983. The Product Life Factor. Orr, Ed. NARC, Texas.

Stahel, W., 1994. The utilization-focused service economy: ressource efficiency and product-life extension, in: Allenby BR, Richards DJ (eds), Greening of industrial ecosystems, National Academy of Engineering, Washington DC, pp. 178-190.

Van Den Bergh, J., 2007. Evolutionary thinking in environmental economics. Journal of Evolutionary Economics 17, 521-549.

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