Innovation strategies and end of life products: an evolutionary modelling

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Abstract. Product design changes are needed to deal with the continuous increase in waste streams. This paper investigates the dynamic of firms’ innovation strategies with respect to the ecological impact of their end of life products. We address this problem 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 firms tend to invest first in product style, then in lifetime and finally in recyclability. Better ecological performance would be obtained if firms invested more both in product recyclability and reliability. Consumers’ preferences and the structure of the innovation potential are found to have an important influence on firms’ R&D choices. Our simulation results suggest introducing regulation policies aiming at getting consumers to change their consumption behaviour and encouraging firms to invest in the development of recyclable products with a long lifetime.

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

JEL Classification: O33, D21, Q53
Introduction

Limiting the 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 in average 550 kg. This statistic is far from the objective of the Fifth European Community environment programme in 1993 which fixed it at 330 kg (Council of the European Union, 1993). The Sixth Environment Action Programme objective is then "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, 2001). Regarding waste, the target is to reduce the quantity going to final disposal by 20% by 2010 and 50% by 2050.

When trying to deal with the continuous increase in waste streams, 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 seems to be 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\(^1\), 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. Today, the tendency is rather to see a fall in product lifetime and, in order to attenuate the ecological impact of their end of life products, firms tend mainly to concentrate more on recyclability (King et al., 2004).

Improvement in product recyclability and in product lifetime involves two different technological solutions (Kemp et al., 1992): end of pipe and clean technologies. End of pipe technologies are equipments added at the end of the production process performing curative treatment once pollution has been created. Clean technologies represent new processes or products that are less polluting than existing alternatives. They involve integrated

\(^1\) 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).
modifications of the core production process leading to a reduction of pollution at source (Saint Jean, 2005). In terms of product innovation, end of pipe technologies correspond to specific technical and technological improvements of the existing product design (incremental innovations), whereas clean technologies require completely reviewing product design in order to develop a new less polluting product (radical innovations). Clean technologies would provide better ecological progress than end of pipe technologies, but they are more complex and costly to implement.

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 ecological performance of the economy. The question will then be to study firms’ strategic choices regarding the characteristics of their products while these firms are interacting with consumers and recyclers. How R&D strategies of firms change? What are the main determinants of these strategies? How do they impact on waste management and ecological 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.

The model:

Before describing the model, a warning note is required. Our goal is not to build a realistic model, but a model that can provide us with insights. 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 model presented here is then a basic model and many aspects of reality are intentionally neglected. The structure of the model is based on the ”History-friendly” model by Malerba, Nelson, Orsenigo and Winter (1999). We used the same kind of topography to characterize products and we modelled innovation and market dynamics in a similar way. But we focused our approach on the environmental dimension of the product and thus introduced the post-consumption phase into the system to be able to study the management of end of life products and consequences of this on ecological variables. We took into account three categories of actors: firms (i) all marketing a single generic finished product\(^2\), 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.

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 style 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.

\(^2\) Consequently, \(i\) represents the product as well as the producer.
The style of the product reflects its esthetism, i.e. the colour, the shape etc. Each product is designed according to a specific style. Each firm will improve it to make its product more attractive towards consumers. $X$ is limited by a fixed upper limit $X_{\text{max}}$ reflecting the maximal performance on this dimension.

$R$ is the recyclability degree of the product. This reflects its environmental performance. 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. We are presuming that there is a $R_{\text{max}1}$ 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 (end of pipe technologies). This means that $R_{\text{max}1}$ 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 (clean technologies). Thus, any firm will be able to exceed $R_{\text{max}1}$ only by offering a new product based on a new design (design for recycling). $R$ is limited by a fixed upper limit $R_{\text{max}2}$.

The reliability of the product is reflected by its lifetime. It reflects any firm’s ability to extend the lifetime of its product. We are also presuming that there is a $LT_{\text{max}1}$ 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 $LT_{\text{max}1}$, the product lifetime can be increased with the initial product design through incremental innovations. $LT$ is limited by a fixed upper limit $LT_{\text{max}2}$.

![Fig. 1. Product's quality attributes](image)

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

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3 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).
or several dimensions, but less efficient on the other(s). However, these effects are not systematic and are not wanted by firms. Moreover, 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.

### Firms’ R&D investment

Each firm invests for each period in R&D a fixed proportion (µ) of its profits (Π) for the previous period\(^4\). R&D investment seeks to improve the quality of any product and, consequently, its visibility (see *Supply-demand interactions*). 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. R&D is divided into expenditure aiming at increasing the product’s style (RD\(^X\)), its lifetime (RD\(^LT\)) and its recyclability (RD\(^R\)):

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

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

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

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.

### The innovation process

The successive R&D investments lead to accumulate knowledge about each of the three quality dimensions. This accumulated knowledge (S\(^X\)) 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 style performance (Prob\(^X\)) are logistic functions of the knowledge level reached in terms of style (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:

\[
\Delta X_{i,t} = \alpha_X \cdot (S_{i,t}^X)^\gamma \cdot (X_{\text{max}} - X_{i,t-1})^\gamma \cdot (E_{i,t})^\gamma \quad (2.a)
\]

This equation implies that the value of the increase in \(X\) depends on the knowledge level reached in terms of style, the distance of the achieved design to the frontier and the cumulated

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\(^4\) µ is a firm specific parameter.
experience \((E)\). 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:

\[
\Delta LT_{i,t} = \alpha_{LT} \left( S_{i,t}^{LT} \right)^{\gamma_1} \left( LT_{\max} - LT_{i,t-1} \right)^{\gamma_2} \cdot (E_{i,t})^{\gamma_3} \quad (2.b)
\]

with \(LT_{\max} = LT_{\max 1}\) if \(LT_{i,t-1} \leq LT_{\max 1}\) and \(LT_{\max} = LT_{\max 2}\) if \(LT_{i,t-1} > LT_{\max 1}\).

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

\[
\Delta R_{i,t} = \alpha_R \left( S_{i,t}^R \right)^{\gamma_1} \left( R_{\max} - R_{i,t-1} \right)^{\gamma_2} \cdot (E_{i,t})^{\gamma_3} \quad (2.c)
\]

with \(R_{\max} = R_{\max 1}\) if \(R_{i,t-1} \leq R_{\max 1}\) and \(R_{\max} = R_{\max 2}\) if \(R_{i,t-1} > R_{\max 1}\). On the other hand, if the innovation draw is a failure, performance remains unchanged\(6\).

The experience \(E\) will decrease at several critical moments of the dynamic. In fact, when a firm adopt a new product design; i.e. when the firm cross the threshold \(LT_{\max 1}\) and/or \(R_{\max 1}\); 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 then useless to develop the new product.

### Supply - demand interactions

In this model, consumer behaviour is simplified. In fact, no interaction between consumers is assumed and consequently, the social aspect of consumer’s decision making is intentionally neglected.

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 whereas it is still in working order because the style of this product does not satisfy its expectations any more. The obsolescence probabilities are based then on a comparison of the style \(X\) 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 products’ visibility \((V)\):

\[
V_{i,t} = \left( X_{i,t} \right)^{\beta_1} \cdot \left( \frac{LT_{i,t}}{P_{i,t}} \right)^{\beta_2} \cdot \left( \frac{R_{i,t}}{MS_{i,t-1}} \right)^{\beta_3} \quad (3)
\]

\(^5\) 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.

\(^6\) Parameters \(\gamma_1, \gamma_2\) and \(\gamma_3\) are the same in the equations \((2.a), (2.b)\) and \((2.c)\).
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 whose values are selected so that the sum of the three is equal to 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. (2003) 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. 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 \( \beta_1 \).

As environmental characteristics are often difficult to observe and reliability is difficult to estimate when buying a product, we assume that consumers cannot know perfectly the objective value of products’ recyclability and lifetime. \( \tilde{LT}_i \) is then drawn from a normal distribution \( N(\tilde{LT}_i, \sigma_{LT}) \) and \( \tilde{R}_i \) is drawn from a normal distribution \( N(\tilde{R}_i, \sigma_R) \) (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. Two subsets of consumers will be considered: "rich" and "poor" consumers. Maximum prices of rich consumers are higher than those of poor.

### 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 suppliers external to the model. To produce the quantity \( Q \), the firm needs a quantity \( \omega.Q \) of recycled inputs and a quantity \( (1 - \omega).Q \) of virgin inputs. \( \omega \) is the share of recycled inputs constituting the product. This variable 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.

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7 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.
The recycler offers for each period a quantity $Z_s$ of recycled inputs. If the recycler offers a sufficient quantity of recycled inputs to face the demand, each firm buys the quantities of recycled and virgin inputs desired. If the recycler does not offer a sufficient quantity of recycled inputs to satisfy the whole of the demand, he will sell off the whole of his stock, the distribution between firms being carried out according to their requirements in recycled inputs. Then, each firm facing a recycled inputs shortage will buy in an additional quantity of virgin materials. Consequently, we assume that there is no constraint in the quantity of virgin inputs.

We determine then the product unit cost of production ($CM_t$) to fix its selling price. The selling price of the product is defined as a minimum price ($p_{min}$) 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 $LT_{i,t} \leq LT_{max1}$, the firm markets a product with a short lifetime design. In this case $p_{min}$ is equal exactly to the unit cost of production of the previous period:

$$p_{min, i,t} = CM_{i,t-1} \quad (4.a)$$

If $LT_{i,t} > LT_{max1}$, the product is designed to have a long lifetime design. In this case an extra cost ($AddC_t$) appears in the production process and so $p_{min}$ is higher:

$$p_{min, i,t} = CM_{i,t-1} \{1 + AddC_{i,t}\} \quad (4.b)$$

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 Product’s characteristics). 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 $AddC_t$. In fact, once the firm crosses the $LT_{max1}$ 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. The first draw has been presented previously (see The innovation process). Regarding the second draw, if it is a success, the fall in the value of the extra cost will be given by:

$$\Delta AddC_{i,t} = \alpha_{AddC} \cdot S_{i,t}^{LT} \cdot \gamma_1 \cdot (AddC_{i,t-1})^{\gamma_2} \cdot (E_{i,t})^{\gamma_3} \quad (5)$$

$\alpha_{AddC}$ is a scale parameter and the parameters $\gamma_1$, $\gamma_2$ and $\gamma_3$ are the same than those used in the equations (2.a), (2.b) and (2.c).

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

**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\(^8\), 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 \(LT_{max1}\) and adopt a long lifetime product design, and \(AC\_{R}\) when the firm crosses the threshold \(R_{max1}\) and adopt a design for recycling. These costs will be borne by the firm over several periods following the adoption\(^9\) 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. This 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.

### 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 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 (\(\Pi_{\text{max}}\) and \(\Pi_{\text{min}}\)):

\[
\text{Pr}_{ob_{\text{change}}} = k \left(1 - \frac{\Pi_{t,t} - \Pi_{\text{min}}}{\Pi_{\text{max}} - \Pi_{\text{min}}} \right)
\]

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:

\[
\begin{align*}
\delta_{i,t}^X &= \min \left[1, \max \left(\delta_{i,t-1}^X + \Delta \delta_{i,t}^X, 0\right)\right] \\
\delta_{i,t}^{LT} &= \min \left[1, \max \left(\delta_{i,t-1}^{LT} + \Delta \delta_{i,t}^{LT}, 0\right)\right] \\
\delta_{i,t}^R &= \min \left[1, \max \left(\delta_{i,t-1}^R + \Delta \delta_{i,t}^R, 0\right)\right]
\end{align*}
\]

with

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\(^8\) i.e. when the firm's product lifetime and/or recyclability become greater than \(LT_{max1}\) or \(R_{max1}\).

\(^9\) \(AC_{LT}, AC_R\) and the duration of payment are identical for all the firms.
\[ \Delta \delta_{X,i,t} \sim N(0, \sigma) \]
\[ \Delta \delta_{LT,i,t} \sim N(0, \sigma) \]
\[ \Delta \delta_{R,i,t} \sim N(0, \sigma) \]

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.

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\(^{10}\). 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\(^{11}\). 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\(^{12}\).

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 Firms’ R&D investment and The innovation process). 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 lead to accumulate 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.

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 \( (\omega) \) 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.

The model defined in this manner enables, by means of simulations, a study of the evolution of firms’ innovation strategies and changing trends in waste production and recovery.

\(^{10}\) Thus, starting from a unit of product, the recycler manufactures and sells \( R \) units of recycled inputs.

\(^{11}\) We are assuming that the part which cannot be recycled is incinerated or stocked in a waste disposal site.

\(^{12}\) 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…).
Simulation results

Experimental set-up

We used the LSD 5.6 simulation platform\(^\text{13}\) 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 methodology close to the 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 space. To analyse the simulations results we used box plots, Wilcoxon-Mann-Whitney tests and regression trees\(^\text{14}\).

Dynamic of firms’ innovation strategy

The analyse of the innovation strategies regarding products characteristics shows that firms prefer investing above all in product style (figure 2). In fact, the part of the total R&D investment allocated to product style (\(\delta^X\)) tends to be the highest one. The second part is the one allocated to product lifetime (\(\delta^T\)), and the smallest is the part allocated to product recyclability (\(\delta^R\))\(^\text{15}\). This result is explained by the fact that investing in product style provides high economic performance (profits, market share) with a low risk of bankruptcy. Investing in product lifetime provides high economic performance too, but the probability to exit the market is higher due to the fixed adoption cost \(AC^{LT}\) related to the radical changes needed both in product design and in production structure when the firm extends its product lifetime. Concerning product recyclability, investing in this dimension is also more risky because of the fixed adoption cost \(AC^R\), and moreover, it provides a low economic performance because green demand is in general not much developed.

\[\text{Fig. 2. Box plots of the firm’s distribution choice of R&D expenditure}\]

\(^{13}\) http://www.business.aau.dk/~mv/Lsd/lsd.html

\(^{14}\) We used Eviews 5 and R to analyse the simulations results. Interested readers may obtain a full copy of the detailed results of the Wilcoxon-Mann-Whitney tests by writing to the author.

\(^{15}\) These results are confirmed by the corresponding Wilcoxon-Mann-Whitney tests.
Such a distribution choice of R&D expenditure favours sharp improvement in product style to the detriment of product reliability and recyclability. Consequently, ecological performance of the economy will be lower than it would be if the parts allocated to product lifetime and/or recyclability were higher. In fact, improvement in products' lifetime will lower waste streams and virgin materials flows. Improvement in products' recyclability will lower the unrecycled part of end of life products which is incinerated or stocked in a waste disposal site and will lower pressure on natural materials by creating a recycled materials supply. As regards recycling activity, improvement in products lifetime would lower the quantities of waste to recycle and so it would slow down the recycler production. But at the same time, improvement in product recyclability will increase the recyclable part of this waste. These first results and arguments call for more investigation into the main determinants of the firms' innovation strategies regarding their product characteristics.

**Determinants of firm innovation strategy**

We investigated these determinants with the help of regression trees. These trees give a hierarchical sequence of conditions on the variables of the model: the higher the role of a condition in the classification of the observed case, the higher its status on the tree (Venable and Ripley, 1999). For each condition, the left branch gives the cases for which the condition is true and the right branch gives the cases compatible with the complementary condition.

The regression trees show that the main determinants of the firms’ innovation strategies are the consumers’ preferences. In fact, the main determinant of $\delta^X$ (figure 3) is the non-green consumers' preferences with respect to product style ($\beta_1$): a high value for this parameter will lead to a greater value for $\delta^X$. The highest expected part (0.4102) is obtained when $\beta_1$ of non-green consumers is high ($\geq 0.4896$) and when the share of green consumers on the market is low ($Green\_Share < 0.3382$). The main determinant of $\delta^{LT}$ (figure 4) is $\beta_2$. This parameter reflects the consumers' preferences with respect to product use cost. A high value for this parameter will lead to a greater value for $\delta^{LT}$. In the same way, the main determinant of $\delta^R$ (figure 5) is the non-green consumers' preferences with respect to product recyclability ($\beta_3$) and a high value for this parameter will lead to a greater value for $\delta^R$.

The composition of demand seems to be also crucial. Figures 3 and 5 show that the share of green consumers ($Green\_Share$) is an explanatory factor of $\delta^X$ and $\delta^R$: a high share tends to lower the part of R&D investment allocated to product style and to increase the part allocated to product recyclability. This observation is confirmed by the box plots of the figure 6. We call "Green demand" ($G$) the configurations for which the number of green consumers is higher than the number of non-green, and "non-green demand " ($NG$) those for which the

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16 A regression tree establishes a hierarchy between independent variables using their contributions to the overall fit ($R^2$) of the regression. It splits the set of observations into sub-classes characterized by their values in terms of their contribution to the overall fit and their predictions for the dependent variables. This value is validated against a fraction of the sample that is not used during the estimation.

17 For example, in figure 3, on the left branch, we have all observations for which $Beta1\_Non\_Green < 0.4896$ and on the right branch, we have all observations for which $Beta1\_Non\_Green \geq 0.4896$. When $Beta1\_Non\_Green < 0.4896$ and $Beta2 \geq 0.5116$, the expected value of $\delta^X$ is 0.315 and we have $n = 1295$ observations corresponding to this case.

18 The higher $\beta_1$, the greater the consumers' preferences with respect to product style.

19 The use cost of a product can be defined as its cost per period of use, i.e. its price divided by its lifetime. The higher $\beta_2$, the greater the consumers' preferences with respect to use cost.

20 The higher $\beta_3$, the greater the consumers' preferences with respect to product recyclability.

21 The composition of demand will impact on the distribution choice of R&D expenditure between the investment allocated to product style and the investment allocated to product recyclability. The R&D investment allocated to product lifetime seems to be independent of the share of green consumers.
situation is reversed. Box plots shows that the greening of consumption leads to invest more in product recyclability to the detriment of product style ($\delta^R$ increases, $\delta^X$ decreases and $\delta^{LT}$ is stable). When demand is green, we can observe no significant difference between the three shares: the R&D investment is equally allocated among the three quality dimensions.

In other respects, the characteristics of the innovation potential for the lifetime and the recyclability dimensions are found to play a major role in the dynamic of the firms’ innovation strategies. A high value for $LT_{max1}$ tends to increase $\delta^{LT}$ (figure 4)\(^{22}\) and lower $\delta^R$ (figure 5)\(^{23}\). A low value for $LT_{max1}$ means that incremental improvements of the initial design can provide just a small rise in product-lifetime. Radical changes in the product design and the production process are needed to significantly extend the product’s lifetime. Inversely, when $LT_{max1}$ is high, product-life extension does not require such radical changes. Incremental innovations are enough to reach a high level in product lifetime which encourage firms to invest more in this dimension and less in product recyclability. Firms would invest more in this last dimension when $R_{max1}$ is high (figure 5)\(^{24}\) because in such a case, firms can easily increase their product recyclability and consequently their product visibility since no radical changes in product design are required\(^{25}\).

Fig. 3. Determinants of the part of the total R&D investment allocated to product style ($\delta^X$)

\(^{22}\) This effect comes into play when $\beta_2$ is high.
\(^{23}\) This effect comes into play when $\beta_i$ of non-green consumers is low.
\(^{24}\) This effect comes into play when $\beta_i$ of non-green consumers is high.
\(^{25}\) The characteristics of the innovation potential would impact on the distribution choice of R&D expenditure between the investment allocated to product lifetime and the investment allocated to product recyclablity. Figure 3 shows that $\delta^X$ would be independent of the characteristics of the innovation potential.
Fig. 4. Determinants of the part of the total R&D investment allocated to product lifetime ($\delta^{LT}$)

Fig. 5. Determinants of the part of the total R&D investment allocated to product recyclability ($\delta^R$)
In short, demand attributes are the main determinant of the development of firms' innovation strategies. Firms adapt their R&D strategies mainly according to consumer characteristics in order to market the most suitable product. A greening of consumption seems then to be crucial to get firms to invest in the environmental quality of their products.

**Impact of demand characteristics on the ecological performance of the economy**

Environmental performance of products will depend on consumer characteristics and consequently, demand attributes will impact on the ecological performance of the economy. The simulation experiments show that greening of consumption; i.e. an increase in the consumer's preference with respect to product recyclability ($\beta_3$) and/or an increase in the share of green consumers on the market; will lead to improve the products' recylability. Consequently, it will increase the recycled share of waste streams and then lower the part incinerated or stocked in a waste disposal site. However, greening of consumption will not lower waste streams, and it would even increase these flows because firms will concentrate more on product recyclability and less on product lifetime. This change in firms' R&D strategies will in addition increase pressure on virgin resources because of the shorter lifetime of products.

In order to avoid this phenomenon and to lower waste flows, another change in demand's characteristics would take place. Waste streams will decrease if consumer's preference with respect to product use cost ($\beta_2$) increase. In fact, a higher value for $\beta_2$ will encourage firms to invest more in product lifetime (figure 4) which will in term lead to lower quantities of end of life products each period. This result can be observed on figure 7$^{26}$ (the Wilcoxon-Mann-Whitney test shows significant difference between the Low and the High cases). Furthermore, it will lower pressure on virgin resources because quantities of products to manufacture each period will be lower.

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$^{26}$ The "Low" cases are the configurations for which the value of $\beta_2$ is lower than the second quartile of its distribution and the "High" cases are the configurations for which the value of $\beta_2$ is higher.
Consumers’ budgetary constraints would also impact the waste streams’ dynamic and put pressure on natural resources. In fact, long lifetime products are in general more expensive because of the additional expenditure related to the more rigorous quality control the firm has to implement (see The production process). Consequently, some consumers cannot buy these products because their maximum price is too low. An increase in consumers’ maximum prices would then increase the quantities of long lifetime products sold and so lower waste streams and pressures on virgin resources. However, such a rise in maximum prices will also enable some consumers excluded from the market to enter it and buy a product, which will increase the quantities of products sold over each period and in turn the waste streams and the virgin material flows. Figure 8 shows that this last effect prevails in our experiments. In fact, when there is a majority of rich consumers, waste streams and pressure on virgin resources are higher.

Fig. 7. Box plots of waste streams according to consumer’s preference with respect to product use cost ($\beta_2$)

Fig. 8. Box plots of waste streams and virgin materials flows according to consumer’s budgetary constraints

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27 The selling price ($p$) of long lifetime product is in general higher but their use cost ($p/LT$) tends to be lower due to their longer lifetime.

28 The “Low” cases are the configurations for which the share of rich consumers (consumers with a high maximum price) is lower than 50% and the “High” cases are the configurations for which the share is higher than 50%.
As regards recycling activities, the greening of demand would lead to lower recycler profits\(^{29}\). In fact, the increasing quantities of recycled materials will lead to an overproduction which will in turn lower the price of these materials. This effect underlines the problem of overabundant quantities of recycled materials which may occur when demand is not sufficient. Nevertheless, we have to notice that we consider here a closed system. A part of the recycler's supply could then be exported to other industries, reducing this phenomenon.

Lower recycler's profits would also be obtained when consumer's preference with respect to product use cost (\(\beta_2\)) increase because of the improvement in product lifetime leading to lower quantities of end of life products to recycle. On the contrary, recycler's profits will be higher when the share of rich consumers rises. In fact, in such a case, supply and demand for recycled materials will be higher\(^{30}\) leading to a rise in price as in quantities sold.

### Conclusions

The model presented in this paper 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 firm's innovation strategies regarding product characteristics.

First, the model dynamics show that firms prefer investing, first in product style, then in lifetime and finally in recyclability. However, in order to obtain a high ecological performance in the economy (low waste streams with high recyclable rates) high investment rates both in product recyclability and lifetime are needed. In fact, improvement in recycling is a necessary but not a sufficient condition to solve the issue of waste growth. Recycling needs to be combined with an extension in product-life to face increase in waste.

Our experiments show that these changes in R&D strategies would be obtained by changes in consumers' preferences concerning both their sensitivity to a product's environmental performance and its reliability. In fact, the model dynamics show the major impact of consumer preferences on the R&D trajectories of firms, and in turn on the ecological performance of the economy.

These results underline that local authorities should introduce regulations aiming at encouraging consumers to change their behaviour and getting firms to invest more in product recyclability and lifetime. Kemp et al. (1992) show that regulatory and public pressures have a great impact on development of clean technologies. Environmental constraint is in general initiated by regulatory authorities or public pressure "so that, if firms are to innovate, then they must do so with respect to certain performance parameters" (Saint Jean, 2005). Present regulations on waste, notably those based on extended producer responsibility (Lindhqvist, 2000), are mainly related to products like packaging, electric and electronic equipments or end of life vehicles. It is then, worth asking whether or not, as they stand, such regulations are likely to produce the type of radical changes required such as those our findings would suggest.

\(^{29}\) This effect occurs when the share of green consumers increases. The increase in \(\beta_2\) will not impact on recycler's profits.

\(^{30}\) An increasing share of rich consumers will lead to a rise in demand on the market because the number of consumers excluded will decrease. Consequently, the quantities of products to manufacture will rise implying a higher recycled materials demand. In addition, this last demand will be higher because better recycler's profits will allow to improve sharply the quality of recycled materials. The larger quantities of products sold will improve firms' profits and in turn the quality performance of their products, in particular their recyclability. This better products' recyclability combined with the larger waste streams will lead a higher recycled materials supply.
References


