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Durability of consumption goods and market competition: An agent-based modelling

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Durabilité des biens de consommation et marché concurrentiel : une modélisation multi-agents

Résumé

Cet article présente un modèle de simulation multi-agents qui explore la dynamique de durée de vie des produits sur un marché concurrentiel. L'objectif principal de cet exercice de modélisation est d'étudier les conditions sous lesquelles une stratégie d'allongement de la durée de vie des produits peut être efficace. Dans ce modèle, le changement dans les caractéristiques des produits s'opère selon un processus stochastique endogène qui repose sur les interactions entre des firmes et des consommateurs hétérogènes. La contribution principale de cet article est de proposer une modélisation détaillée de la demande permettant d'analyser plus en profondeur comment les décisions de consommateurs dotés d'une rationalité limitée peuvent influencer la dynamique du système et, en particulier, comment leur processus d'achat agit sur les stratégies des firmes ainsi que sur la sélection qui s'opère sur le marché. Tandis que la plupart des travaux portant sur la durée de vie des produits étudient le marché d'un monopole, notre modèle met en avant au contraire que la concurrence et la diversité comptent. La coexistence sur le marché de produits concurrents présentant des durées de vie hétérogènes est à même d'inciter les firmes à allonger la durée de vie de leur produit. Nos résultats mettent également en évidence le rôle clé des processus gouvernant la décision d'achat des consommateurs au sein de la dynamique de marché. Le comportement d'achat des consommateurs en lui-même guide les stratégies des firmes et in fine façonne la structure du marché.

Mots-clés : dynamique industrielle ; obsolescence; durabilité des produits; durée de vie des produits; modèle de simulation; consommation durable

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Abstract

This paper presents an agent-based simulation model that explores the dynamics of product lifetimes on a competitive market. The main objective of this modelling exercise is to investigate the conditions under which product-life extension strategies can be effective. In this model, change in products' characteristics is driven by an endogenous stochastic process relying on the interplays between heterogeneous consumers and firms. The main contribution of the paper is to present a detailed modeling of demand which enables to analyze more thoroughly how decisions of bounded rational consumers impact on the dynamics of the system and, more particularly, how purchase process shapes market selection and strategies of firms. While most existing literature on product lifetime investigates durable goods monopolists, our study highlights that competition and diversity matter. The coexistence of competing products with different lifetimes can encourage firms to market long lifetime products. Our results also stress the critical role played in market dynamics by the processes driving purchase decision. The purchasing behavior of consumers in itself will greatly guide firms' strategies and in fine shape market structure.

Keywords: industrial dynamics; obsolescence; product durability; product lifetimes; simulation model; sustainable consumption

JEL: O33, D11, D21, Q57

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1. Introduction

Products' lifetime is a critical aspect of consumer society and growing environmental concerns make this factor a key issue for sustainable consumption.

We define product's lifetime as the period over which the product is used by its owner(s). This is the physical lifetime of the product. We will focus in this paper on durable products defined as consumption goods that do not quickly wear out. They yield utility over time rather than being completely consumed in one use. Typical examples are cars, home appliances or consumer electronics.

Consumer may drop out its current product to buy a new one for two main reasons: because it is out of order or because it does not satisfy consumer's expectations anymore. In fact, every consumer is characterized by a requirement level concerning its product attributes (Simon, 1955, 1956), and when its product no longer meets this requirement level, consumer may want to change it in order to acquire a new product more consistent with its preferences (Katona, 1975; Van Raaij et Gianotten, 1990; Marell *et al.*, 1995).

Despite growing attention about environmental consequences of consumption[1], there is no recent empirical study measuring product-life trends (Cooper, 2004, 2005). The last comprehensive study dates from 1982 (OECD, 1982). The main reason is the lack of available data (Antonides, 1990; Conn, 1977; Cooper, 1994; OECD, 1982). According to Bayrus (1998, p.764) *"Empirically, it is very difficult to rigorously examine product lifetimes, since detailed data for the entire product life-cycle and at all the various product market levels are generally difficult to acquire. Consequently, very limited empirical information on product lifetimes for any particular industry is available in the literature".* In recent years, some assessments of product lifetimes have been undertaken in relation to waste reduction (Cooper, 1994; Heiskanen, 1996), the marketing of long lifetime products (Kostecki, 1998) or second-hand markets (Gregson and Crewe, 2003; Thomas, 2003), but empirical research in this area remains poor. Even if there is no empirical proof based on large data base (Bayrus, 1998), most existing studies show that product lifetimes are declining (Kostecki, 1998; Cooper and Mayers, 200; Slade, 2006). The main current problem is that firms and consumers tend to replace their products more and more frequently leading to increasing quantities of waste and to greater pressure on natural resources. The rapid development of mass production and consumption goes with increasing product obsolescence which will *in fine* shortens the product replacement cycle both by firms and consumers (Reisch, 2001; Nelson, 1967; Dhebar, 1995; Fernandez, 2001). For instance, during a typical five year period, two thirds of U.S. manufacturing firms switch their products (Bernard *et al.*, 2003), while in Japan consumers replace their phone cell in average every year (Slade, 2006). While a large part of firms shorten their products' lifetime (deliberately or because of acceleration of technological and styling changes), some competitors implement the opposite strategy, that is extending product's lifetime. Typical examples are Dyson and Kia offering extended warranty for their products, or Aura which markets high pressure sodium lamps with an estimated lifetime of 48.000 hours while most of competitors' lamps last up to 15.000 hours. It is attractive, therefore, to consider under which conditions product-life extension strategies could be effective in a competitive market. This is the main purpose of this article which explores the dynamics of product lifetimes in an agent based simulation model. In this model, change in products' characteristics is driven by an endogenous stochastic process relying on the interplays between heterogeneous consumers' attributes and firms' strategies. Noting that the demand side of markets is generally neglected in literature on market dynamics, we developed a detailed modeling of

[1] See for instance Lorek and Spangenberg (2001), Noorman and Uiterkamp (1998), OECD (2002).

demand which enables us to analyze more thoroughly how consumers' attributes impact on the dynamics of the system and, more particularly, how purchase process shapes market selection and strategies of firms. This is done in a bounded rationality context *à la Simon* (Simon, 1982) in which agents facing uncertainty are not able to optimize their choice. Our purpose is to test in such context the relative dynamic efficiency of product-life extension strategies.

The paper is organized as follows. In section 2 we present the key issue of product obsolescence and the role of demand. In section 3 we present the model. In section 4 we present some simulation results with an increasing degree of complexity in the assumptions so as to both understand the basic dynamics of the system and to exhibit general findings. In section 5 we draw some final conclusions.

2. Product obsolescence and demand

The key factor explaining the shortening of product replacement cycle is product obsolescence. Product obsolescence can be defined as the relative loss in value due to quality improvements or styling changes in subsequent versions of the product. *"In markets where technological improvements and styling changes are frequent, product obsolescence is an important phenomenon because consumers are reluctant to invest in a product that can soon be superseded"* (Levinthal and Purohit, 1989, p.35). In this way, the decline in product lifetimes can be explained by the acceleration of technological and styling changes. It leads consumers to change more frequently their product to hold the most up to date version. Firms can also deliberately design a product with a limited useful life, so it will become obsolete after a certain planned period. Planned obsolescence strategy aims to generate long-term sales volume by reducing the time between repeat purchases. The rationale behind this approach is that additional sales revenue would more than offset both the additional costs of research and development needed to develop a new product and opportunity costs of existing product cannibalization. This can be a risky strategy in a competitive industry because consumers may decide to buy a longer lifetime product from competitors. Because of this, planned obsolescence strategy would be effective in monopolistic or oligopolistic markets and/or if consumers are fooled on the actual cost per use of the product in comparison to the competitors.

Many theoretical models focus on this question. They investigate optimal durability (Swan, 1970, 1971; Sieper and Swan, 1973) and establish the conditions under which it would be optimal for the monopolist to switch its current product. They focus on time inconsistency (Coase, 1972; Bulow, 1982, 1986; Waldman 1993, 1996a; Choi, 1994; Fishman and Rob, 2000), adverse selection (Akerlof, 1970; Hendel and Lizzeri, 1999a), network externalities (Waldman 1993, Choi, 1994) or new product introductions with technological change (Levinthal and Purohit, 1989; Fudenberg and Tirole, 1998; Lee and Lee, 1998)[2]. Existing literature on durability choice investigates durable goods monopolists in two-period equilibrium models to distinguish new and used products. They generally conclude that durable goods monopolist typically underinvests in durability so that products' lifetime is below its optimal level (Waldman, 1996b; Hendel and Lizzeri, 1999b; Kim, 1989; Anderson and Ginsburgh, 1994). *"By reducing durability below the efficient level and thus the quality of used units below that level, the monopolist reduces the substitutability between new and used units, which, in turn, allows the firm to increase the price of new units"* (Waldman, 2003, p.138). Since the presence of some monopoly power is crucial to their arguments, these models invariably study monopoly markets. *"However, obsolescence appears to be a feature that also arises in industries that have competitive elements (even though they may not be perfectly competitive), such as the often-cited example of annual model changes in the automobile industry"* (Grout and Park, 2005, p.596). In addition, since they almost consider only two time period, these models cannot generate extended industrial

[2] For an extended review on these models see Waldman (2003).

dynamics that would be used to investigate how and why firms' strategies and consumers' behavior evolve through time. It is attractive, therefore, to study the product-life factor in a competitive market where firms and consumers interplay over a large number of time periods. This is the purpose of this article. Most of literature on market dynamics focuses on the supply side of markets and demand is either neglected or considered exogenous. For this reason, studies on technological change generally assume homogeneous products. We propose in this paper a more detailed modeling of demand enabling us to study heterogeneous consumers facing heterogeneous products. In fact, consumers are not passive spectators in product obsolescence phenomenon. They play an active role trough their preferences about products features. In the current mass consumption context, consumers want more, better, faster (Slade, 2006) and contribute then to shorten the product replacement cycle by demanding to own the newest product to date. In particular, consumers increasingly assign to product a "novelty value" associated with owning a brand new product (Stahel and Jackson, 1993). In this context, agents often change their current product, not because it is worn out or defective, but because they are tired of it (Van Hinte, 1997; Cooper, 2005). But at the same time, some consumers can give special importance to product reliability or durability and will be more inclined to buy long lifetime products, giving rise to a niche market for such products. Heterogeneity in consumers' attributes is then a crucial aspect of market selection. By offering the opportunity to model interactions between heterogeneous agents over a large number of periods, agent-based modeling is an efficient tool to propose a relevant representation of market dynamics.

The consumer's modeling proposed in the following is based on Simon's bounded rational behavior (Simon, 1982). Consumers are assumed to not consistently select the optimal product maximizing their utility. In fact, most final consumer purchases concern goods with relatively minor significance in respect to the overall life of a person and in general consumers are not perfectly informed on all the different features of the product they purchase. In addition, when consumers buy the "wrong" product (i.e. a dominated alternative compared to the optimal choice), there is no economic penalty which could push them to either correct their choice or to leave the market. Consequently, consumers can be assumed to not devote a lot of time and attention to collect and use all the relevant information about available products' features in order to make optimal purchase decision. They rather behave following specific satisficing rules which could lead them to select a suboptimal alternative, more expensive or with a lower quality than the optimal choice, but far easier to be decided upon[3].

The demand model proposed sheds light on firms-consumers interactions that will shape market dynamics. In particular, it will enable us to explore the conditions leading to effective product-life extension strategies. The model that follows is kept as simple as possible so that we can easily focus on this particular question.

3. The model

We consider the market of a generic durable product. We take into account two categories of agents: firms (i) producing and marketing finished products and end consumers (j) buying those products. Every firm is assumed to supply one single type of product at the same time[4] and every consumer is assumed to use one single product at the same time. There is nor exit of agent neither entry of new agent in the model.

[3] For a more detailed discussion on this question see Valente (2003a, 2003b).

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

Product modelling

Every product is modelled as a vector of characteristics which determine its quality level (Lancaster, 1966; Saviotti and Metcalfe, 1984). Every characteristic is represented by a positive real number; the higher this number, the higher the product performance on this particular characteristic. In this paper we assume that products are defined by three characteristics: their cheapness, defined as the inverse of price (1/p), their technical quality (X) and their reliability, defined as their lifetime (L).

X is a multi-criterion dimension reflecting the performance of the technical attributes of the product during the use phase. X is a synthetic index which increases in proportion to the overall technical quality of the product.

L is the maximum number of periods over which the product can be used. For instance if L = 2, the product can be used over 2 consecutive periods, then it breaks and must be replaced.

We assume a positive relation between technical quality and price and also between reliability and price: the higher the technical quality and/or the reliability of the product, the more expensive it will be. In this paper, we do not focus on the supply side and consequently, in order to not unnecessarily complicate the model, we consider a very simplified production process. In particular, we do not focus on the processes occurring in firms' strategies to set their price. We consider a very simple price setting process and we model price by applying the very simple following rule:

$$p_{i,t} = X_{i,t}.L_{i,t} \quad (1)$$

Following this equation, for a given level of technical quality, the price per period of use is identical for all the products. Note that the absolute values for products' qualities are not important because the procedure used (see "Purchase decision process") requires only to compare for each characteristic whether one product is superior, inferior or equivalent to another product. In this way, a product is absolutely superior to another one only if all the values constituting its vector of characteristics are superior to all the values in the vectors of the other competing products. Such a representation allows to take to into account trade-offs amongst product characteristics since some products will score better than competitors on certain characteristics but worse on others.

The whole set of values in the vectors of characteristics are chosen so that all the products available satisfy the minimal conditions for being considered for an actual purchase by all consumers. In particular, prices are set so that they do not exceed reserve price of any consumer.

Purchase decision process

As noticed in section 2, we model consumer decision in a bounded rationality context à la Simon in which consumers are assumed to follow satisficing rules which could lead them to buy a suboptimal product, but far easier to be decided upon.

In our model we assume that each consumer purchases and then uses one single product at the same time. Consumers renew their product only when this product is at the end of its lifetime (L) or when it becomes obsolete. In fact, we assume that consumers can renew their product (before its end of life) when it is still in working order because the technical quality (X) of this product do not satisfy their expectations anymore. Thus, renewal decisions rely on satisficing rules: only consumers owning a product with an unsatisfactory level of technical quality will choose to change it. The modelling of these renewal decisions is based on obsolescence probabilities depending on the technical quality (X) of the products currently used by consumers in the current period. The higher the technical quality of the product, the less likely it will be considered as obsolete. Thus, consumer j will replace its product before its end of life according to the following obsolescence probability ($prob^{Obs}$):

$$prob^{Obs}_{j,t} = x.\left(1 - \frac{X_{j,t} - MinX_t}{MaxX_t - MinX_t}\right) \qquad (2)$$

X_j is the technical quality of the product owned by consumer j, MinX and MaxX are the best and the worst technical quality of the products currently used by consumers on the market in the current period and x is a parameter reflecting the maximum obsolescence probability[5].

This product renewal will have a negative impact on the environment. In fact, each time a consumer renews its product, the old one becomes an end-of-life product which increases the quantity of waste to be collected and treated. In addition, manufacturing the new product will consume energy and resources which will increase the environmental burden. We have to notice that we take into account neither the environmental impact of the product during its use phase nor its recyclability. In fact, if the new product is more energy efficient than the old one or if it is made with less unrecyclable materials, this will have a positive impact on the environment. As we only focus on the product-life factor, we will not take into account these effects[6].

Product-life extension could lead to rebound effects since, compared to short lifetime products, long lifetime products will give their owners the opportunity to save money over the additional period of use and this money can then be spent to buy other (polluting) products. As we consider a single market and we assume that consumers own one single product at the same time, this issue will not be explicitly discussed in our model.

When buying a new product, consumers will make their choice depending on their preferences with respect to products' characteristics: X, L and 1/p. In fact, in our model consumers are over all defined according to their preferences towards products' characteristics. To simplify the model dynamics we assume that preferences are exogenous and cannot change trough time[7]. The crucial point is to determine how to explicitly represent the choosing process. Gigerenzer and Goldstein (1996) argue convincingly that human behavior regarding decision making can be represented by the Take-The-Best strategy (TTB). This strategy is indeed supported by experimental observation of actual people's behavior and it appears to be very efficient when facing uncertainty and poor available information. In our case, we consider the choosing process consisting of selecting one product among several options, each defined over a set of characteristics. The TTB strategy is then composed by the three following steps (Valente, 2003b):

1. The consumer evaluates the available products on the only basis of her preferred product characteristic.

2. If one single product scores highest in respect of that characteristic, the consumer chooses this product.

3. Otherwise, if more than one option scores similarly, the consumer removes the dominated options and restarts from 1. with the second preferred characteristic.

[5] Consumers owning a product with the highest performance will have an obsolescence probability equal to zero, those owning a product with the lowest performance will have the maximum probability x.
[6] For a more detailed discussion on product recyclability and lifetime see Brouillat (2009a, b).
[7] For a detailed discussion on preferences origins and for a modeling of endogenous consumers' preferences see Valente (2003a, 2003b).

Consumer's individual preferences are then defined as the order in which characteristics are used in the TTB strategy. We assume that each consumer can establish a ranking on products' characteristics depending on their relative importance in the purchase decision. We will then consider six possible ranking representing six consumer preferences sets (table 1).

Table 1. Consumer categories

Consumer category	A	B	C	D	E	F
Ranking on products' characteristics	X > L > 1/p	X > 1/p > L	L > X > 1/p	L > 1/p > X	1/p > X > L	1/p > L > X

It is possible that at the end of the TTB process there are still several remaining products. In this case, we assume that the consumer will choose randomly its product amongst these remaining options. Regarding this random draw we will test two possibilities. In the first one, every remaining product has the same probability to be chosen. In the second case, we take into account a bandwagon effect (Lebeinstein, 1976) where every remaining product has a probability to be chosen proportional to its market share. This bandwagon effect reflects social influences in the purchase decision since consumers will prefer products that are more diffused.

The TTB algorithm respects the principles of bounded rationality and is in line with the experimental evidence that, facing different alternatives, people resolve the conflict by selecting the alternative that is superior on the more important dimension (Shafir et al, 1993; Slovic, 1975, 1990; Tversky et al, 1988).

An important point is that this type of choosing process does not allow compensations amongst product's characteristics. That is, a weak product on the first characteristic will be removed even if it is very powerful on the other characteristics. In particular, if consumers are almost "price oriented" buyers, long lifetime but expensive products can be quickly discarded even if they are cost effective in the long run, i.e. their price per period of use (p/L) is the same than cheaper short lifetime products.

Nevertheless, when evaluating the available products in respect of a characteristic, we assume that consumers use a tolerance margin to compare each alternative with the optimal one. We call the generic value v_i^k the measure of product i in respect of characteristic k, v_{max}^k the optimal level on characteristic k, and m the tolerance margin (with m in the range [0;1]). If $v_i^k \geq m.v_{max}^k$ the product i is considered equivalent to the optimal one on the characteristic k ($v_i^k \approx v_{max}^k$). So, the lower m, the more consumers are "tolerant". This tolerance margin is used by consumers to avoid discarding products that are very slightly inferior in the first stages of the TTB algorithm but much better in respect of further aspects (Valente, 2003b). It is also a way to take into account imperfect information and bounded rationality which will prevent consumers to perfectly identify the best available product on a given characteristic.

Once the consumer has bought the product of his preference, she becomes a customer of the selected firm. From the firm's point of view, each time its product is bought, an additional sale is recorded and its stock of customers will increase by one unit. On the other hand, when one of its customers decides to change its product, the firm records a loss and so its stock of customers will drop by one unit. At the end of the purchase cycle, each firm counts the number of sales (Q) and the number of lost users (LOST) and consequently determines the current number of users of that product, i.e. its stock of customers (U):

$$U_{i,t} = U_{i,t-1} + Q_{i,t} - LOST_{i,t} \quad (3)$$

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

$$S_{i,t} = \frac{U_{i,t}}{\sum_{i=1}^{n} U_{i,t}} \quad (4)$$

Firm strategy

To not needlessly complicate the model, we limit the dynamics at work on the supply side. As we noticed previously every firm is assumed to supply one single type of product at the same time. We model an adaption process where firm's strategy consists in choosing freely the characteristics of its product; i.e. the level of its technical quality and its lifetime; within a given admissible range. We assume that this operation is free of cost and is instantaneous: once the firm has chosen the features of its product, it is able to market it. We do not model any innovation process consisting in gradually improving product's characteristics.

Firms' strategies may change over time in order to fit their behaviour to the fluctuations of the market environment. In fact, depending on market feedbacks and their economic performance, firms may decide to change their product feature to increase their market share. Firms' strategies are then characterized by a learning process divided into two steps (Silverberg and Verspagen, 1995). The first step determines if the firm wants to change its product's characteristics, while the second fixes the new characteristics adopted. This learning process is based on a Simonian approach of bounded rationality so that firms take their decisions according to satisficing rules: only the firms with unsatisfactory market share levels will choose to change their strategy. Firms will decide then to change their strategy with probabilities proportional to their market share (S_i) and the best and the worst market share observed on the market in the current period (Smax and Smin):

$$Prob_{i,t}^{Change} = \alpha.\left(1 - \frac{S_{i,t} - Smin_t}{Smax_t - Smin_t}\right) \quad (5)$$

Parameter α is the maximal probability. Thus, the higher its market share, the less likely the firm will change its strategy. If the draw is a success, the firm will review its strategy; if not, the firm retains its strategy from the previous period.

Once the firm has decided to change its strategy, it randomly selects a firm in the economy with probabilities proportional to firms' market share. Once the firm has chosen the competitor to imitate, it adopts the strategy of this firm by imitating the value of its product's features X and L and markets then the same product.

4. Simulation results

We will present in this section successive simulation experiments with an increasing degree of complexity[8]. The objective is first of all to understand the basic dynamics of the system before gradually complicating the model to obtain more relevant and general findings. We will study several

[8] We used the Laboratory for Simulation Development platform to compute and run the model. This simulation platform is develop by Marco Valente (2008) and is downloadable for free at the following address: www.labsimdev.org.

successive model settings, from the simplest to the most complex. In every model setting, we formalize 1200 consumers. The number of firms will depend on the model experiment.

Tolerance margin and "capturing effect" of demand

The objective of this first experiment is to consider the most simplified version of the model to investigate its very basic dynamics.

In this simulation experiment, we formalize 4 firms. We assume that firms' strategies are fixed ($\alpha = 0$ in equation 5). In other words, firms cannot change the characteristics of their product. These characteristics are presented in table 2. On this basis, we will distinguish two types of firms: those marketing short lifetime products (firms 1 and 3) and those marketing long lifetime products (firms 2 and 4).

Regarding the demand side, obsolescence probabilities are null for all the consumers ($x = 0$ in equation 2). Consequently consumers renew their product only when this product is at the end of its lifetime. There is also no bandwagon effect: if there are still several remaining options at the end of the TTB, every remaining product has the same probability to be chosen.

Table 2. Distribution of products characteristics

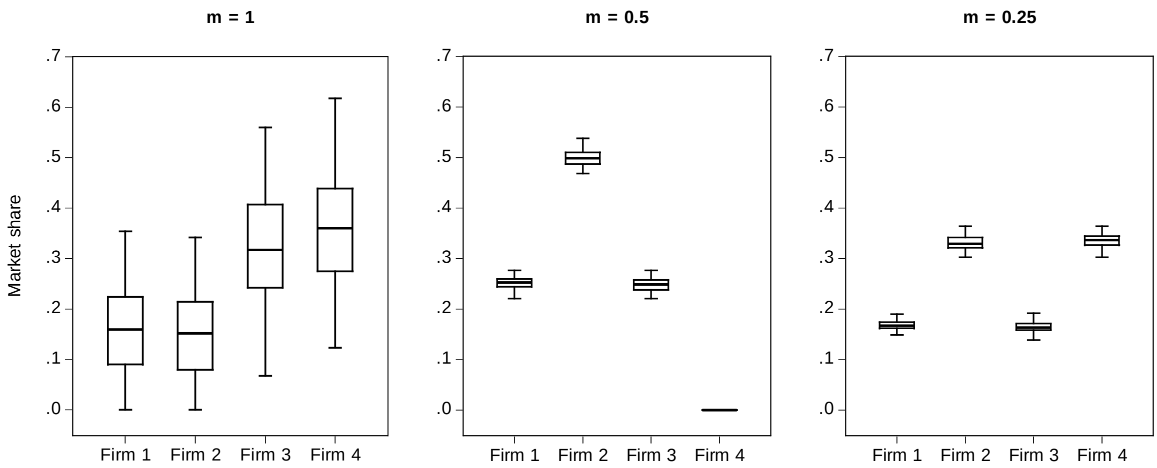
		Firm 1	Firm 2	Firm 3	Firm 4
Product's characteristics	Technical quality (X)	2	1	1	2
	Lifetime (L)	1	2	1	2
	Price (p)	2	2	1	4

We will consider three values for the tolerance margin of consumers: m = 1, 0.5 and 0.25. In each case, we run 100 simulations of 50 periods each with an initial random draw for the relative share of each consumer category (table 1). We will discuss simulation results using boxplots[9].

Boxplots on figure 1 represent the distribution of firms' market shares. When m = 1, consumers can perfectly identify the best available product for a given characteristic. In this case, they can perfectly identify the product which fits the best with their first preferences and they will always select the same product. Consequently firms' market shares are fixed for a given simulation run. Consumers A and C always buy the product of firm 4, consumers B the product of firm 1, consumers D the product of firm 2 and consumers E and F buy the product of firm 3. If we note z_h the share of consumers h in the total population of consumers (h = {A, B, C, D, E, F}), the distribution of firms' market shares is the following: $S_1 = z_B$; $S_2 = z_D$; $S_3 = z_E + z_F$; $S_4 = z_A + z_C$. There is no uncertainty about the economic performance of firms: they only depend on the relative share of each consumer category. Thus, the dispersion in firms' market shares is only explained by the difference in the relative share of each consumer category across the 100 scenarii.

[9] A boxplot gives the quartiles of the distribution of the considered variable as well as its maximal and minimal values. We control significant differences between series with Student T tests.

Figure 1. Firms' market shares (S)

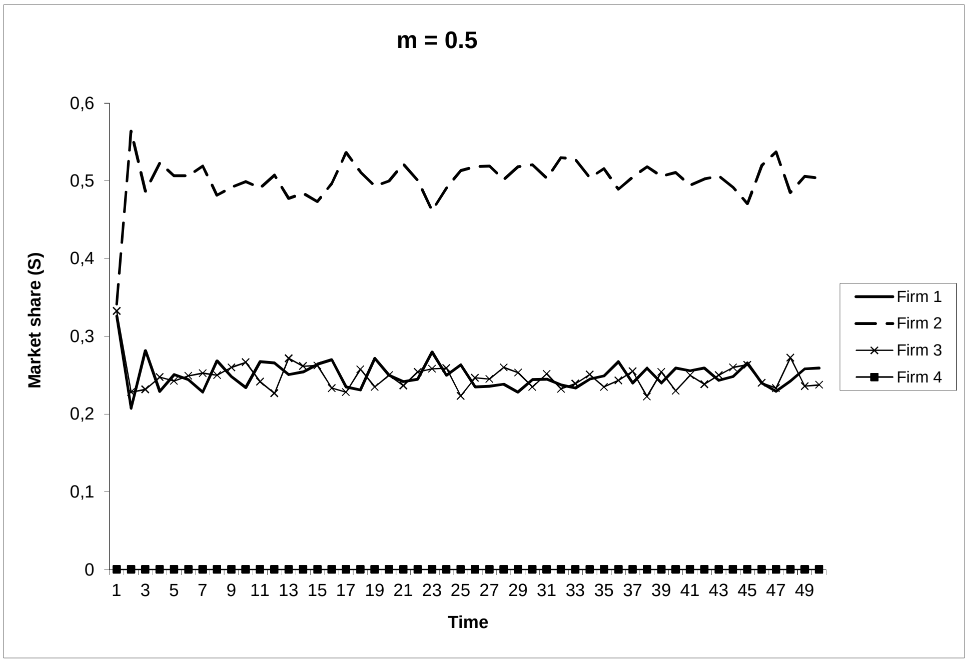


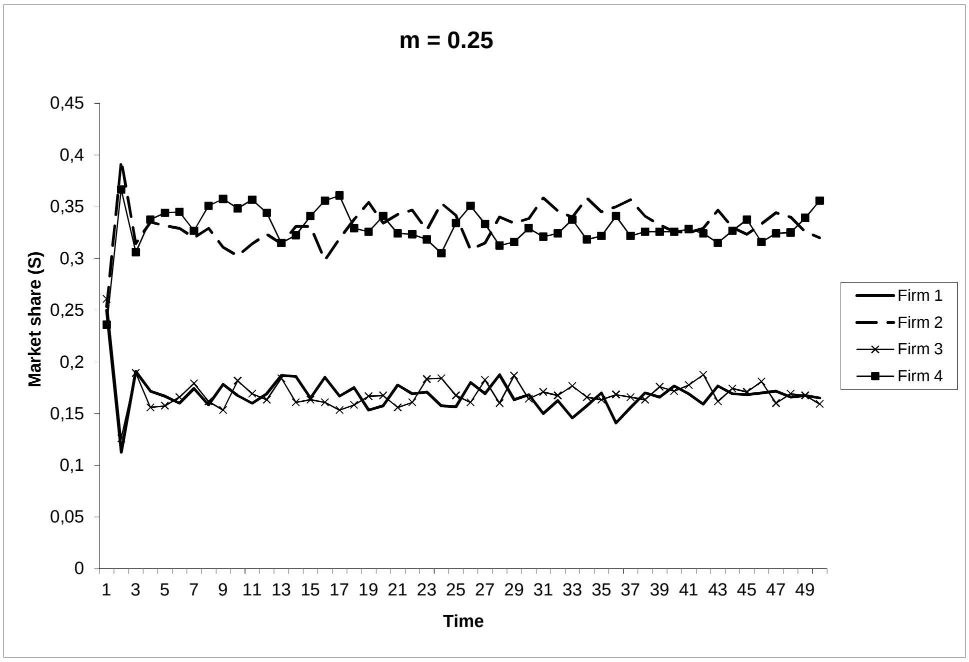
When m = 0.5, the threshold values under which products are removed are 1 for X and L and 0.5 for 1/p. All the firms market a product with X and L ≥ 1, but firm 4 is the only one with 1/p < 0.5. Consequently, the product of firm 4 is always discarded and its market share is null. The three other competitors will share the total demand, but we observe that the market share of firm 2 is much higher than those of firm 1 and 3. This better economic performance is directly linked to the longer lifetime of its product. This makes it possible to keep customers over a longer period given that they will not be captured by other firms during the time they are using that product. Over the same period, firm 2 can "capture" customers from firms marketing shorter lifetime products, namely firm 1 and 3. Customers belonging to these firms have to renew their product more often and so, they will tend to be, more often than not, in search of a new product. Consequently they will be inevitably more inclined to be captured by other firms. Thus, whatever the distribution of consumer categories, firm 2 can manage to gain much greater customer numbers. We will call this phenomenon the "capturing effect". By focusing demand on long lifetime products, this effect reduces dispersion in market shares. In other words, the capturing effect reduces the impact of consumers' preferences on firms' economic performance.

When m = 0.25, the threshold values under which products are removed are 0.5 for X and L and 0.25 for 1/p. Consequently, whatever consumers' preferences, no product is removed and there are still the four competing products at the end of the TTB process. Consumers will randomly choose their product amongst these four options with equal probabilities. We can observe that firms 2 and 4 manage to obtain higher market shares thanks to the capturing effect related to the longer lifetime of their product, as explained above.

These very first results clearly denote that the success of product-life extension strategies will sorely depend on the level of the tolerance margin. In particular, they show that long lifetime products can be successful even if there is no direct demand for this type of product. In fact, if we consider the particular case where product lifetime is a first-class purchase criteria for no one ($z_C = z_D = 0$ and $z_A = z_B = z_E = z_F = 0.25$), when consumers have no tolerance margin (m = 1) the market share of firm 2 is obviously null. But when consumers have a tolerance margin (m = 0,5 or m = 0,25), the capturing effect comes into play and the market share of firm 2 far exceed those of firms marketing a short lifetime product, even if product-life remain at best a second-class purchase criteria (figure 2).

Figure 2. Trends of firms' market shares (S) with no direct demand for long lifetime products

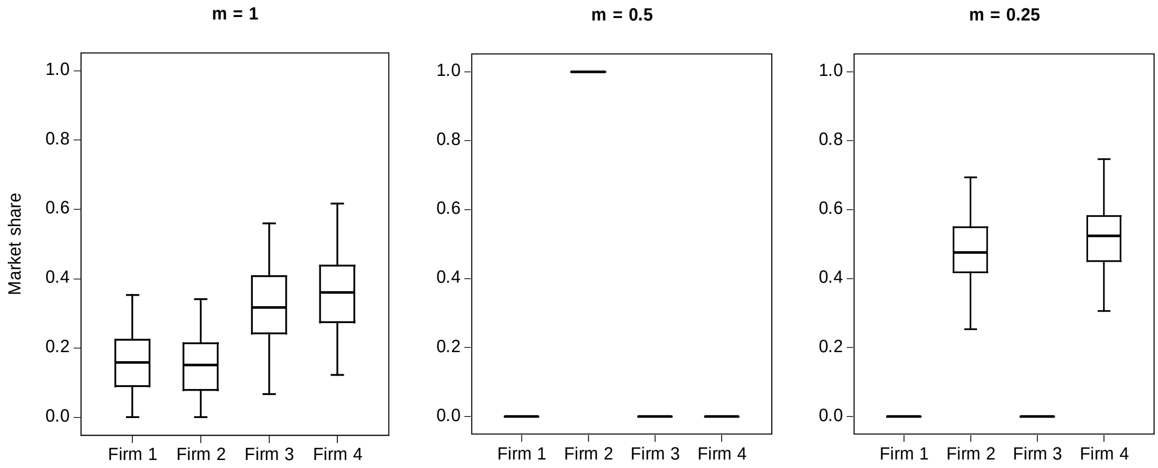




This first experiment highlights how the purchase decision process of consumers impacts market dynamics. Consumers' preferences (their ranking on products' characteristics) are obviously a key factor, but our results also emphasize the crucial role played by the basic mechanisms leading the purchase decision. They are reflected in particular by the tolerance margin parameter. By introducing a degree of uncertainty in the purchase choice of consumers, this margin gives rise to a capturing effect of demand, which will have critical impact on economic performance of firms, in particular those marketing long lifetime products. We have to notice that diversity in firms' strategies is a determining factor in the dynamics as the capturing effect appears only if there are several available products with different lifetimes. If all the products on the market exhibit the same lifetime, the effect totally vanishes.

We add now a band wagon effect to take into account social influences in the purchase process. The band wagon effect intensifies the capturing effect of product-life extension (figure 3) since at the end of the TTB process every remaining product has a probability to be chosen proportional to its market share.

Figure 3. Firms' market shares (S) with band wagon effect



The economic advantage of firms marketing long lifetime products is reinforced leading to a firm 2 monopoly when m = 0.5 and to a firm 2 – firm 4 symmetric duopoly when m = 0.25[10].

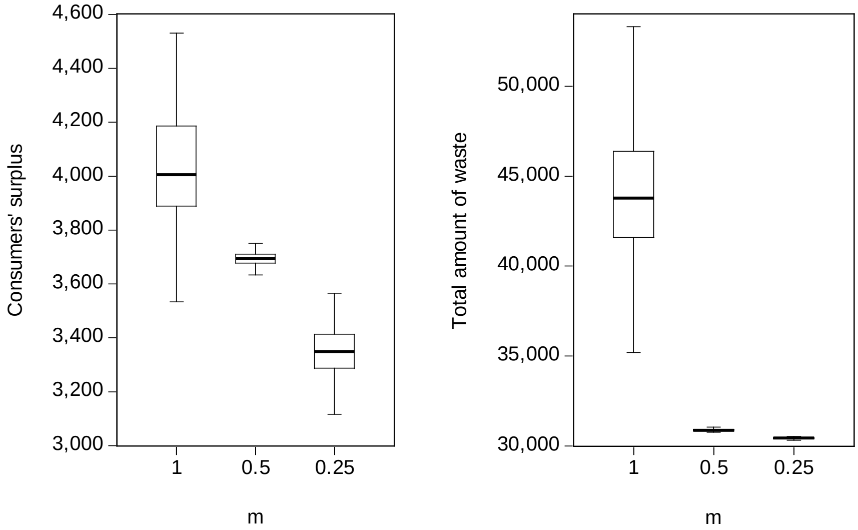
This market domination of long lifetime products will have direct influence on consumers' welfare (figure 4). Consumers' surplus will be impacted. It is a purely pecuniary indicator of welfare since individual surplus is calculated as the difference between the reserve price of the agent and the price of the product purchased at the current period[11]. To not unnecessarily obscuring the basic logic of the model, we assume that all consumers have the same reserve price which is the price of the most expensive product on the market, so that each consumer can buy any available product. Since long lifetime products are more expensive (see equation 1), their diffusion leads to a decrease in consumers' surplus which will have negative impact on their welfare. However, only considering pecuniary surplus as a measure of welfare is a very narrow vision. Consumers' welfare also depends on non-pecuniary aspects, in particular environmental protection. By reducing the amount of waste (figure 4), the diffusion of long lifetime product will have a positive impact on the environment and in turn on welfare, which will counterbalance its negative effect on surplus. Nevertheless, we do not try to aggregate pecuniary surplus and environment protection to calculate a synthetic quantitative estimation for the net impact of long lifetime products on consumers' welfare. In fact, estimating the weights of the different heterogeneous elements that enter into the assessment of welfare is a very complex and arguable issue which is beyond the scope of this article[12].

[10] The Student T test with 1% probability shows no significant difference between the two series Firm 2 and Firm 4.

[11] This means that if the consumer does not buy any product over the period, its surplus is maximal, equals to its reserve price.

[12] Moreover, this task is even tricky than we model products with heterogeneous technical qualities. This will have an impact on welfare since owning a high-tech product would provide greater satisfaction than owing a low-tech one, *ceteris paribus*.

Figure 4. Consumers' welfare indicators



Product obsolescence

Starting from the previous configuration of the model, we will investigate is this section the impact of product obsolescence on market dynamics. To this end, we will consider two levels for the parameter x reflecting the sensitivity of consumers to product obsolescence: a low value (x = 0.1) and a high value (x = 0.9).

Regarding economic performance of firms, product obsolescence has no impact on the dynamics when m = 1: firms' market shares are fixed because every consumer will always select the same product. When consumers have a tolerance margin, product obsolescence will affect the distribution of market shares (figure 5). If m = 0.5, only a high sensitivity of consumers to product obsolescence will impact the market structure: firm 2 will share the demand with firms marketing short lifetime products (firms 1 and 3), but the market domination of firm 2 remains very strong. If m = 0.25, as in the previous case, only firms marketing long lifetime products (firms 2 and 4) will share the demand, but product obsolescence will lead now to unbalanced market shares. In fact, due to the difference in the technical quality of their products, sensitivity of consumers to obsolescence will favour firm 4 whereas it will handicap firm 2. The more they are sensitive to product obsolescence, the more customers of firm 2 will change their product before its end of life and the more likely they will be to be captured by firm 4. In other words, product obsolescence reinforces the capturing effect of product-life extension for firms marketing a high-tech product. We obtain then a firm 4 monopoly when consumers are very sensitive to obsolescence (x = 0.9).

From an environmental point of view, figure 6 obviously shows that product obsolescence increase the amount of waste, which will negatively affect agents' welfare. The best situation is obtained with a large tolerance margin and a low sensitivity to obsolescence (m = 0.25 and x = 0).

Figure 5. Firms' market shares (S) with product obsolescence

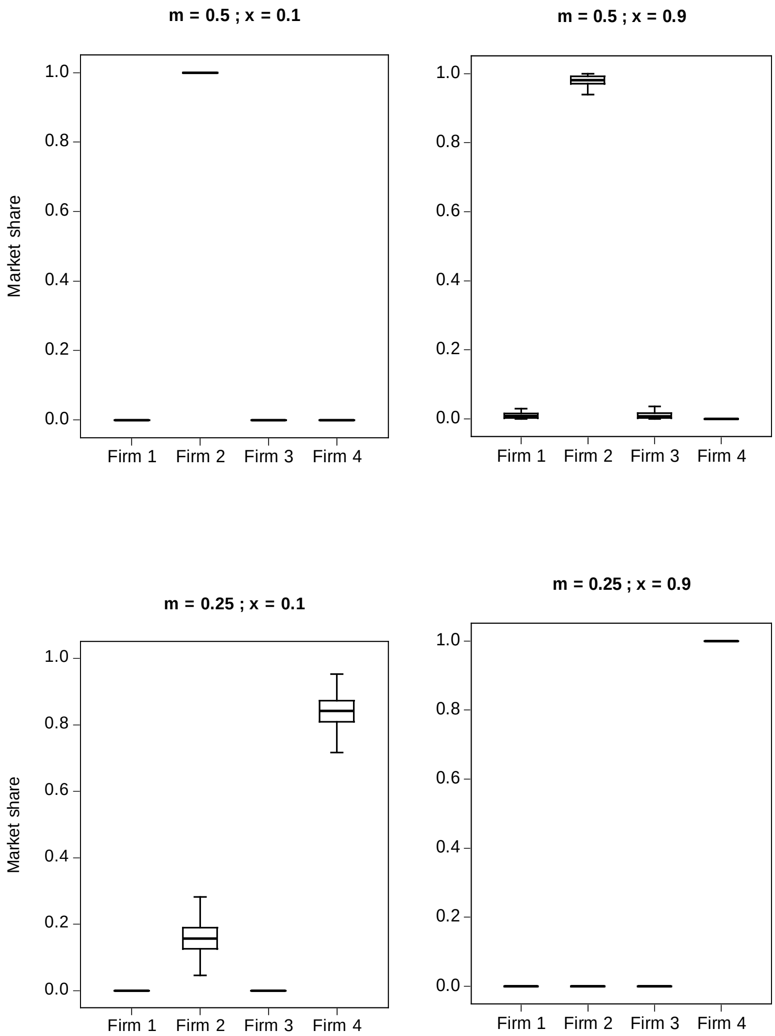
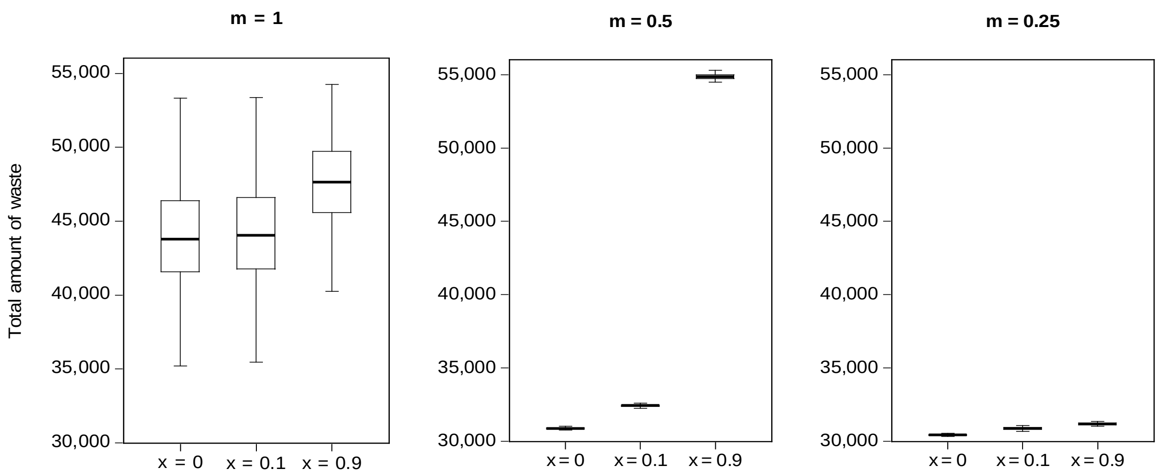
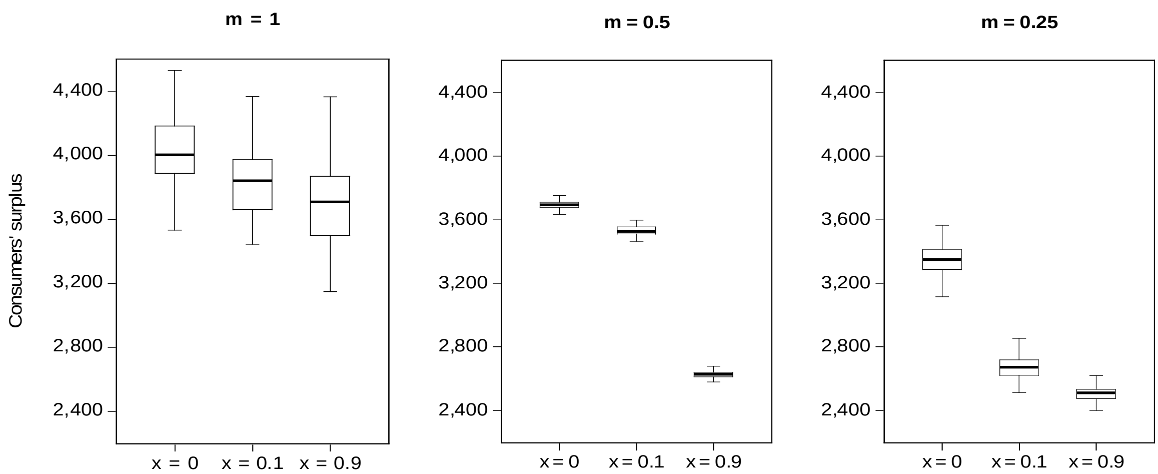


Figure 6. Total amount of waste



The average technical quality of the products sold will mechanically rise with the sensitivity of consumers to obsolescence, which would have a positive impact on their welfare. But regarding consumers' surplus, figure 7 clearly shows that product obsolescence has a negative impact since it encourages consumers to both renew more frequently their product and select first and foremost more expensive high-tech goods. Even if these goods would provide greater satisfaction than low-tech goods, one can reasonably think that the negative effects of product obsolescence on the environment and consumers' surplus would dominate, leading in the end to a global negative impact on consumers' welfare.

Figure 7. Consumers' surplus



We will investigate in the next section a more complex configuration of the model in order to complete these first findings and draw more general conclusions.

Monte Carlo simulations

In this simulation experiment, we will explore the properties of the model with a wide range of parameter settings. The purpose is to identify some emergent properties and results which can be considered as valid for the whole set of parameters. To this end, we will present the results coming from a battery of 5000 simulations carried out with a Monte Carlo procedure. This methodology enables us to run a high number of simulations with a random setting for the initial values of the parameters. It is a way of exploring the parameter space and of emphasizing the variety of the possible outcomes of the model without an arbitrary initialization of the parameters. In particular, it will enable us to test the effects on the model dynamics of parameters characterizing the demand side and to hold out general proposition about their impact on the market. For each simulation run, we draw parameter values within the admissible ranges presented in table 3.

Table 3. Chosen domain for parameters characterizing the demand side in the Monte Carlo procedure

Parameter	Initial value	description
x	[0 ; 1]	Maximum obsolescence probability (equation 2)
m	[0 ; 1]	Tolerance margin
z_h	[0 ; 1] with $z_A + z_B + z_C + z_D + z_E + z_F = 1$	Share of consumers h in the total population of consumers

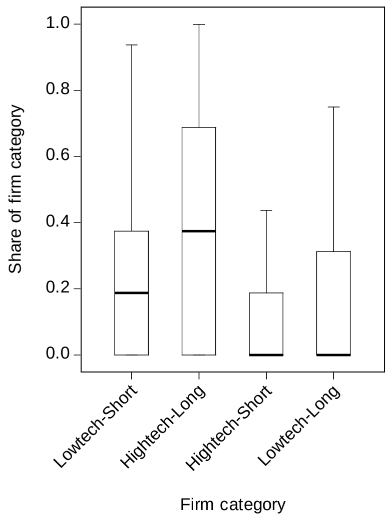
We formalized 16 firms with evolving strategies following the adaptive process described in section 3 (*Firm strategy*)[13]. The strategy of a given firm is defined by the characteristics of its product: X, L and p. At the beginning of each simulation run, every firm will choose randomly the value for the variables X and L and may change it thereafter in order to fit its behaviour to the fluctuations of the market environment. To broaden the spectrum of possible firm strategies, we now assume that variables X and L can take any integer value between 1 and 4. In table 4 we define four firm categories based on their product strategy.

Table 4. Firm categories

<table>
<tr><td colspan="2" rowspan="2"></td><td colspan="4">Lifetime (L)</td></tr>
<tr><td>1</td><td>2</td><td>3</td><td>4</td></tr>
<tr><td rowspan="4">Technical quality (X)</td><td>1</td><td colspan="2" rowspan="2">Low-tech products with short lifetime (Lowtech-Short)</td><td colspan="2" rowspan="2">Low-tech products with long lifetime (Lowtech-Long)</td></tr>
<tr><td>2</td></tr>
<tr><td>3</td><td colspan="2" rowspan="2">High-tech products with short lifetime (Hightech-Short)</td><td colspan="2" rowspan="2">High-tech products with long lifetime (Hightech-Long)</td></tr>
<tr><td>4</td></tr>
</table>

Simulation results show that Lowtech-Short and Hightech-Long strategies are generally preferred by firms (figure 8). In other words, firms will mostly market either a cheap low quality product or on the contrary an expensive high quality good[14].

Figure 8. Distribution of firm strategies



	Lowtech-Short	Hightech-Long	Hightech-Short	Lowtech-Long
Mean	0.245	0.402	0.135	0.217
Median	0.187	0.375	0	0
Maximum	1	1	1	1
Minimum	0	0	0	0
Std. Dev.	0.291	0.366	0.240	0.323

This finding is coherent with our previous results: Lowtech-Short and Hightech-Long products will be inclined to be selected by two categories of consumers (consumers E and F for Lowtech-Short products and consumers A and C for Hightech-Long products) while Hightech-Short and Lowtech-

[13] We run simulations with 500 periods each in order to allow sufficient time for evolutionary processes to implement.

[14] We have to remind that every consumer can potentially buy any product on the market. There is not any income constraint that would prevent some consumers to buy expensive products. Considering such constraint would obviously affect our results.

Long products will be generally preferred only by one single category of consumers (consumers B for Hightech-Short products and consumers D for Lowtech-Long products). This will mechanically give an advantage to Lowtech-Short and Hightech-Long strategies over the 5000 simulation runs. We can also argue that firms would prefer not to adopt the Lowtech-Long strategy because long lifetime leads to market quite expensive products and at the same time low technical quality prevents firms to benefit from the capturing effect of product-life extension because of product obsolescence. They would neither adopt the Hightech-Short strategy for the same reasons: products are quite expensive due to their high technical quality and product-life is too short to generate capturing effect. To resume, in order to benefit from product-life extension by generating capturing effect of demand, firms have to market high-tech products. Otherwise, it is better to market a cheap low-tech product with short lifetime.

Figure 8 shows that firms will generally prefer the Hightech-Long strategy to the Lowtech-Short's because the capturing effect that increase market shares only comes into play with the first strategy. However, these two strategies are complementary. As we have already noticed, if all the products exhibit long lifetimes, the capturing effect totally vanishes. The existence of short lifetime products on the market is then deciding to justify the Hightech-Long strategy. This means that Hightech-Long and Lowtech-Short products will generally coexist and consequently there will not be any dominant design on the market.

To deeper understand these global results and highlight the effects of demand parameters on the dynamics, we will use regression trees (figures 9 and 10). A regression tree (Venables and Ripley, 1999) establishes a hierarchy between independent variables using their contributions to the overall fit (R^2) of the regression. The tree gives a hierarchical sequence of conditions on the variables of the model: the higher the role of a condition in the classification of the observed case, the higher its status on the tree. For each condition, the left branch gives the cases for which the condition is true and the right branch gives the cases compatible with the complementary condition[15].

Trees on figure 9 show that the tolerance margin of consumers will have critical influence in firms' strategic choice. When consumers have a large tolerance (i.e. a low value for m), long product-life strategies will be chosen first because this demand feature allows the capturing effect to be effective. More precisely, the Lowtech-Long strategy will be chosen only if consumers are insensitive to product obsolescence ($x < 0.2661$) and m is not too low ($0.06466 \leq m < 0.4898$). In fact, when the tolerance margin is very large ($m < 0.08349$) the Hightech-Long strategy is chosen by almost all the firms (93.7%). Short product-life strategies will be generally preferred for intermediate values of the tolerance margin, when the capturing effect is weakened. When $0.334 \leq m < 0.4995$, almost 50% of firms choose the Lowtech-Short strategy, while the Hightech-Short strategy is favoured either by a high value for m combined with a large share of consumers B ($m \geq 0.493$ and $z_B \geq 0.1632$) or by an intermediate value for m ($0.1118 \leq m < 0.493$) combined with a high sensitivity of consumers to obsolescence ($x \geq 0.5561$).

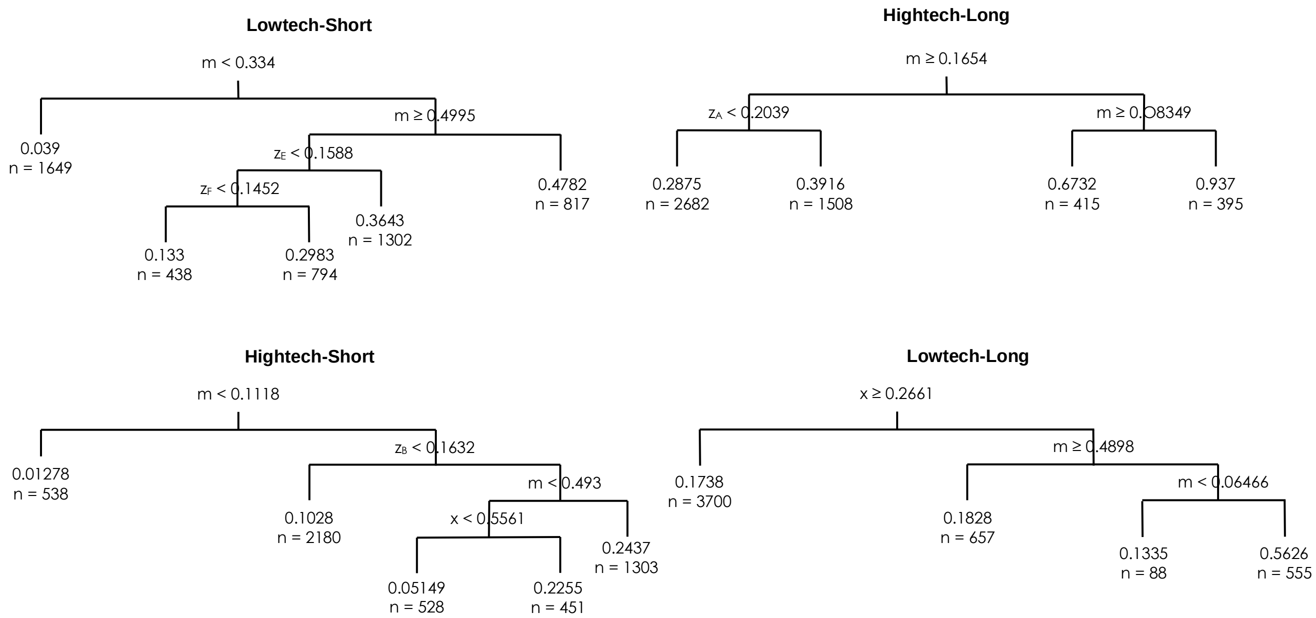
Consumers' preferences appear to be a secondary criterion[16]. No surprisingly, firms will be incited to adopt the Lowtech-Short strategy when demand consist of a quite large number of consumers whose product cheapness is the first-class purchase criterion (consumers E and F) while a large share of consumers A and B will respectively favor Hightech-Long and Hightech-Short

[15] If we consider for instance the Lowtech-Short tree in Figure 9, on the left branch, we have all observations for which $m < 0.334$. On the right branch, we have all observations for which $m \geq 0.334$. When $m \geq 0.4995$ and $Z_E \geq 0.1588$, the expected value for the share of firms on the market selecting the Lowtech-Short strategy is 36.43% and we have n = 1302 observations corresponding to this case.

[16] On each tree, they come into play on branches corresponding to high values for m, that is to say when consumers are less tolerance regarding dominated options at the first stages of the TTB algorithm.

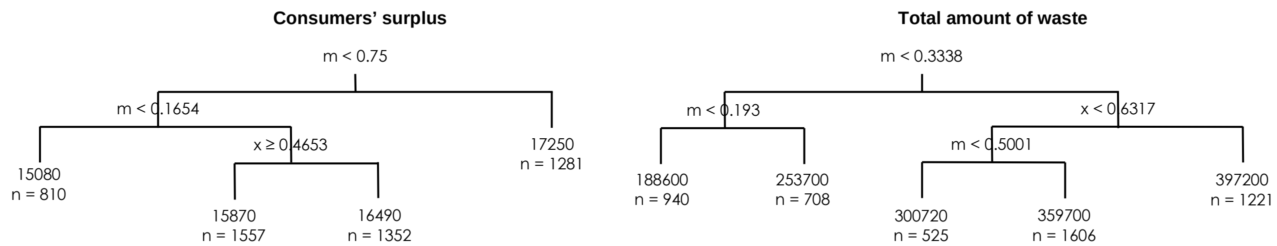
strategies. One can also notice that consumers' preferences do not appear on the Lowtech-Long tree meaning that they are not a critical criterion for firms to choose or not the Lowtech-Long strategy.

Figure 9. Regression trees of firm strategies



In line with these results, trees on figure 10 show that the tolerance margin is the most determining parameter for both consumers' surplus and the amount of waste. We observe that low values for m will lower consumers' surplus because of the large diffusion of expensive Hightech-Long products, but at the same time it increases environmental quality by reducing the amount of waste. Sensitivity of consumers to product obsolescence will also affect these two variables: a high sensitivity will both tend to decrease consumers' surplus and to increase waste streams. Finally, the highest consumers' surplus are obtained when the tolerance margin is low ($m \geq 0.75$) while the lowest values are observed when the margin is large ($m < 0.1654$). In contrast, the best environmental performances are obtained with high tolerance margins ($m < 0.1654$) while the highest waste streams are generated with quite thin margins ($m \geq 0.3338$) and high sensitivity to product obsolescence ($x \geq 0.6317$).

Figure 10. Regression trees of consumers' surplus and total amount of waste



In the end, this more general experiment confirms and supports the findings of the previous simpler model settings showing that market competition and diversity of both supply and demand in a bounded rationality context can lead to efficient product-life extension strategies.

5. Conclusions

We present in this paper an original agent-based model to investigate product-life in competitive markets.

Existing literature on product lifetime investigates durable goods monopolists in two period equilibrium models and generally concludes that firms marketing durable goods typically underinvest in product-life so that products' lifetime is below its optimal level. Our approach differs from these models in several aspects and consequently, our results are rather complementary than conflicting.

We model a competitive market where competition amongst firms occurs over a large number of periods. We focus on the interplays between heterogeneous bounded rational firms and consumers, respectively marketing and buying products modeled as multi-features technologies characterized by their technical quality and their lifetime. We put emphasize on the demand side and we represent the purchase decision making process of consumers by the Take-The-Best strategy (TTB). This model obviously provides a simplified vision of the problem studied. Real world markets are so complex that many aspects of reality have been intentionally neglected and some hypotheses being assumed here are fairly restricted. However, despite this simplification in the modelling, our simulation exercise yields some interesting conclusions about the product-life factor in industrial dynamics.

First of all, our findings clearly point that competition and diversity matter. The coexistence of products with different lifetimes gives rise to a capturing effect of demand for firms marketing long lifetime products: the longer lifetime of their product makes possible both to keep customers over a longer period and to capture customers from firms marketing shorter lifetime products. This capturing effect, by reinforcing the market share of firms choosing to market long lifetime products, will justify this last strategy. But this effect occurs only if there are competing products with shorter lifetimes. If all the products on the market exhibit the same lifetime or if there is just one single firm, the capturing effect vanishes. It will also be effective only if long lifetime products are high-tech products too. In fact, consumers are sensitive to product obsolescence and they will keep their product only if it is not outdated. To be efficient product-life extension strategies have then to primarily involve products with high technical quality.

This means that long lifetime products will tend to be more expensive. Consequently, protecting environment and sustaining consumers' surplus appear to be contradictory objectives. Nevertheless, one can reasonably presume that firms can enjoy economies of scale so that the price of long lifetime products would decrease as they are diffusing in the economy. In addition, the surplus is only one particular aspect of consumers' welfare. Extending product-life will contribute to increase consumers' welfare both by reducing the amount of waste and increasing the technical quality of goods in use.

Our results also highlight the critical role played in market dynamics by the processes driving purchase decision. The purchasing behavior of consumers in itself will greatly guide firms' strategies and *in fine* shape market structure. The TTB algorithm is characterized by a tolerance margin used by consumers to compare each alternative with the optimal one in respect of a given product feature. By substantially shaping the behavior of consumers and *in fine* market dynamics, the tolerance margin is the keystone of the consumers' purchase decision and firms' strategic choice, more than consumers' preferences. In particular, depending on its value, the tolerance margin will give rise or not to the capturing effect of product-life extension, and when consumers are sufficiently "tolerant", marketing long lifetime products is efficient whatever consumers' preferences. Consumers' preferences appear to be a secondary criterion which comes into play when the margin is thin. To resume, the model dynamics emphasize that the effectiveness of product-life extension will depend on consumers' preference towards product lifetime and their sensitivity to obsolescence, but it will first of all rely on the bounded rational behaviour driving consumers' purchase decisions.

This very simple model calls for more research into the modeling of product-life strategies in competitive markets. In particular, extending the modeling of both market supply and demand, but also developing frameworks that take into account public policies would improve our understanding of trends in consumer society and our response to growing environmental concerns.

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