J Evol Econ (2002) 12: 283–306

Journal of Evolutionary Economics

Stimulating diffusion of green products

Co-evolution between firms and consumers*

Marco A. Janssen[1] **and Wander Jager**[2]

[1] Center for the Study of Institutions, Population, and Environmental Change (CIPEC), Indiana University, 408 North Indiana Avenue, Bloomington, IN 47408, USA (e-mail: maajanss@indiana.edu)

[2] Faculty of Business, Department of Marketing, University of Groningen, Landleven 5, 9700 AV Groningen, The Netherlands (e-mail: w.jager@bdk.rug.nl)

Abstract. This paper presents a model-based analysis of the introduction of green products, which are products with low environmental impacts. Both consumers and firms are simulated as populations of agents who differ in their behavioural characteristics. Model experiments illustrate the influence of behavioural characteristics on the success of switching to green consumption. The model reproduces empirical observed stylised facts and shows the importance of social processing and status seeking in diffusion processes. The flexibility of firms to adapt to new technology is found to have an important influence on the type of consumers who change their consumption to green products in the early phase of the diffusion process.

Key words: Diffusion processes – Consumer behaviour – Social networks – Service economy

JEL Classification: D11, D21

1 Introduction

One path in striving towards a more sustainable economy is trying to decrease the amount of materials that is being used. Current economies are focused on consumption of material goods instead of maximising the utilisation of these goods (Stahel, 1994). A transition from this consumptive economy towards a service economy would emphasise the function or service that products may provide instead of emphasising the product itself. Examples are laundry services, car-pooling or

* The first author thanks financial support from the Netherlands Organisation for Scientific Research (NWO) as part of the research programme 'Materials Use and Spatial Scales in Industrial Metabolism' (MUSSIM).

Correspondence to: M. A. Janssen

car sharing services, teleshopping, maintenance services, etc. These service alternatives require important changes in consumer behaviour. When for example you want to wash your cloths, you can buy your own washing machine, or wash your cloths in a nearby laundry service centre. Stimulation of services will require a behaviour change of both the consumers and the service companies. For example, by sharing products, service companies will make it more logical to consider repair or refurbishing of the products as a possible course of action. In order to elicit such a transition, product designs and product services need to change. Products need to be developed in such a way that components can be taken back for re-manufacturing products. Re-manufacturing is different from recycling in that it is a form of product prolongation, not a simple material loop closing (Stahel, 1994).

Closing the product loop requires structural changes in the economy, involving behaviour change of both producers and consumers. Innovative producers may perceive a possible new market share for what we shall call *green products*, and hence may adopt their production process towards making products that fit within this economy, for example, machines that are more robust, reparable and adjustable qua function. Innovative consumers that perceive these products as more attractive may be the first to start using these green products. This may provide a behavioural example for other consumers, whose decision to use the green products may partly originate from social motives.

It is expected that a service economy would be much less material intensive relative to the satisfaction of human needs than the present consumptive economy (Ehrenfeld, 1997). Technically, there are many options to reduce material and energy use by changing product design. The question is why the market entrances of these products so often fail, or require a lot of effort. One likely reason is that production and consumption patterns are often 'locked-in', indicating that the behaviour of the various agents is interdependent or that switching costs hinder behavioural change. Firms are interrelated by competition and profit rates, which makes the large investments in adapting the production process very risky. Consumers frequently feel satisfied when consuming the same as their neighbours (social needs) and often engage in social comparison and imitation when deciding what to consume. Due to these dependencies and processes it can be hard to motivate an individual to change to production/consumption of alternative "green" products.

Due to slow changes of consumption patterns, it is the question how to replace incumbent products with new, more environmentally friendly ones. Taxing of the non-green product is one strategy the government can employ in accelerating the diffusion of green products. In this paper, we assume that various characteristics of products evolve due to interaction with consumers and producers. In fact, consumers and producers co-evolve in order to meet their objectives. Firms invent new products and want to increase their profits, consumers change consumption of a certain product if they expect that it increase their level of need satisfaction. We will observe what effects the imposing of a tax on non-green products has on this co-evolution.

In this paper a simulation model is presented that studies the issue of introduction of alternative products. The multi-agent model describes the behaviour of consumers as well as firms. The behaviour of consumers is modelled in line with simulation models from social psychology (Jager, 2000), while the behavioural rules of the firms are based on evolutionary economics (e.g. Nelson and Winter, 1982).

The paper is build up as follows. In Section 2 a brief overview is presented on the literature of lock-in dynamics and diffusion processes. In Section 3 the simulation model is described and in Section 4 results of model experiments are presented. Section 5 concludes.

2 Lock-in and diffusion dynamics

Although there are products on the market available that seem to be technically superior to existing products, these products often do not obtain a significant market share. To understand this phenomenon, the dynamics of lock-in will be discussed.

Lock-in denotes the situation where a certain technology dominates the market, and it seems to be impossible to introduce an alternative technology. The most popular example to explain this situation is the QWERTY keyboard (David, 1985; Liebowitz and Margolis, 1999). Most people are trained to use a QWERTY keyboard and although it might be more ergonomically efficient to switch to another type of keyboard, which is very simple nowadays with computer keyboards, this is not likely to happen. This is because of the high costs involved in getting used to a new keyboard. Other popular examples are the market dominating software products Microsoft Windows and Word text processing, which make it very difficult for competitors to maintain or expand their market-share due to reasons of limited compatibility.

One economic explanation for a lock-in can be found in price dynamics and increasing returns to scale (Arthur, 1989). The more a product is used, the lower will be the costs per unit of production, which makes the product affordable for more people. This in turn accelerates the market penetration of the product. Such processes can be found in markets with high fixed costs and low variable costs, and in markets where the success of using the technology is dependent on how many other people are consuming or using the technology. Examples of high fixed costs are learning to type on a QWERTY keyboard, developing software, or making a CD. The first copy of a product may costs many millions of dollars, but more copies can be produced at almost no additional costs (Shapiro and Varian, 1998).

When the practical value of a product (returns) increases as a function of the number of people (scale) that use this product, the returns to scale or network effect becomes apparent. Such network effects relate to the use of telephones, faxes, e-mail and software packages, where the practical value increases the more people use these products.

What can be learned from the literature on lock-in is the fact that it can be very hard to replace existing technologies because it will entail a lot of high switching costs (learning a new technology, developing a new technology, adjusting related infrastructure, adjusting existing institutions). As this appears to be an important barrier for the introduction of green products, we will employ a simulation model to investigate how certain aspects in the decision making process of consumers and firms affect the diffusion dynamics of green products. Moreover, using this simulation model we will investigate how financial strategies may interfere with these dynamics.

The diffusion of innovations is a widely studied phenomenon. The innovation diffusion theory as introduced by Rogers (1962) is the most frequently cited publication in this field. Rogers states that the cumulative number of adopters typically follows an S-shaped curve. The S-curve starts to rise slowly when the first *innovators* adopt to the innovation. Following that, the cumulative number of adopters rises somewhat faster due to the *early adopters*. The curve is at its steepest when the *early majority* and *late majority* successively adopt to the innovation. The curve increases at a slower rate when the *laggards* adopt slowly to the innovation. Generally, early adopters appear to weigh their personal needs more, have a higher aspiration level (venturesome fore the innovator and respect for the early adopter; Rogers, 1995, pp. 263–264) and are more actively searching for information (Rogers, 1995, pp. 274), whereas late adopters appear to attach more weight to their social needs, have a lower aspiration level and search less for information. Moreover, early adopters are better in coping with uncertainty than late adopters (Rogers, 1995, pp. 273). This may have consequences for the type of decision process they employ, because people that have a lower tolerance level for uncertainty may engage more in social processing (social comparison, imitation, see also Jager, 2000). Rogers (1995) emphasises the importance of reaching a certain 'critical mass' of adopters beyond which the innovation will diffuse without much stimulation. This is assumed to reflect the importance of having sufficient role models that increase the chance that the innovation is being spotted by less innovative people that engage more in social comparison and imitation. This critical point in the success or failure of a product diffusion is often called a 'chasm' (e.g., Moore, 1991). Especially in high tech markets this 'chasm' separates early markets from mainstream markets (Moore, 1991). We assume that this 'chasm' is primarily being caused by a different weighting of social information by innovators and early adopters (early market) versus the other categories (mainstream market).

The speed and degree to which an innovation diffuses (the slope and top-level of the S-curve) is related to several factors. Rogers (1995, p. 206) states that most of the variance (49 to 87%) in the rate of adoption is explained by five attributes of the innovation: (1) relative advantage, (2) compatibility, (3) complexity, (4), trialability, and (5) observability. In addition to the attributes of the innovation, also factors such as type of innovation-decision, communication channels involved, nature of the social system in which the innovation is placed, and the extent of the change agents' promotional efforts affect the rate of adoption. The general idea is that when an opinion leader has adopted, and a critical mass of adopters is reached (3 to 16%), the innovation will diffuse without much promotion of change agents. Sometimes people may overadopt an innovation, for example, when they innovate because of status reasons whereas the practical applicability of the innovation is relative low. Rogers (1995, p 216) explicitly mentions that this phenomenon should be studied further. We consider this effect of overadoption typically as an outcome of underlying behavioural dynamics. The more people look at the (innovative) behaviour of others as a reference for their own behaviour, the more likely it is that they will adopt the behaviour of these people. Especially when social needs play an important role (e.g., status, belongingness), or when people are uncertain about what to do, they will focus their decision making process on the behaviour of others. However, this may cause them to adopt behaviour that does not satisfy their personal needs all too much. As a consequence, when the social situation changes (e.g., due to fashions), the adopted behaviour may loose much of its satisfactory capability, stimulating people to reconsider their behaviour. This makes clear that the decision process that people use is a critical factor in the innovation diffusion process. When they deliberate a lot they will perceive the innovation in an early stage. When they engage in imitation or social comparison they may learn about the innovation from others. But when they habitually repeat their behaviour they may remain unaware of the innovation. It is evident that the decision processes that characterise a typical market will affect the rate and speed of innovation diffusion to a large extend.

For example, in buying a car people generally deal with important decisions with respect to the amount of money involved and the meaning of a car for one's social identity and status (e.g., Steg and Tertoolen, 1999; Stradling, Meadows and Beatty, 1999). Moreover, people may be uncertain because there is an enormous number of models to choose from, and it is at first unclear how one's social environment perceives the 'personality' of various cars, as well as how this matches with yourself. This explains why people in general talk a lot about cars, and that many magazines and television programmes are devoted to automobiles. The market can thus be seen as dominated by social comparison processes, which may elicit a competitive market with fashion dynamics (see e.g., Janssen and Jager, 2001). This may explain the various trends that can be seen in car design, such as the 'wings' on cars in the 1960s, the popularity of 4-wheel-drives in the 1990s and the current popularity of Multi Purpose Vehicles (MPV's).

The *relative advantage* (economic profitability, social prestige and other outcomes) of an innovation will only be perceived if people take the outcomes of adopting to the innovation into consideration. People are generally motivated to think about alternatives when their current behaviour is not fully satisfactory. Hence, when they are satisfied with their current behaviour they might remain unaware of the innovation and its (changing) characteristics (e.g., decrease of price). Moreover, it appears that relative fast positive outcomes speed up the process of diffusion, whereas preventive and/or distant outcomes lower this rate of diffusion (Rogers, 1995, pp. 216–217). This also makes clear that when people decide, they do not engage in economic optimising (rational actor type behaviour), but rather use more simple heuristics or engage in biased information processing in their evaluation of the relative advantage.

The *compatibility* of an innovation refers to the degree it fits with sociocultural values and beliefs, previously introduced ideas and needs for the innovation. The higher the compatibility of the innovation, the faster its diffusion will proceed.

The *complexity* of an innovation has a negative effect on the rate of the diffusion, although the research is not conclusive on this effect (Rogers, 1995, pp. 242). People that are very motivated to adopt a new innovation (e.g., a computer in the late 1970s) are more likely to spend cognitive effort in understanding this complexity, and hence will be better capable of dealing with it, thus benefiting from the innovation. However, less motivated people that experience uncertainty because of the complexity may decide to buy a computer by observing the outcomes of the early adopters and estimating how they could benefit from using a computer themselves (social comparison). However, these people may experience much more difficulty and frustration in dealing with the innovation than the early adopters, which is in line with the observations of Rogers, Daly and Wu (1980).

The *trialability* of an innovation is affecting its diffusion positively, especially amongst the innovators and early adopters, as these have no behavioural examples of other people that use the innovation (Gross 1942; Ryan, 1948). The more people already adopted the innovation, the less important this trialability becomes, because the experience of other people (social capital) can be employed in deciding to innovate.

The *observability* of the innovation is considered to be positively related with its adoption (Rogers, 1995, pp. 244). Here we want to add that this observability relates to the innovation use, which may be public or private, and to the proportion of people that already adopted the innovation. As regards the latter, especially the people that base their decisions on social information may perceive a low proportion of people using the innovation as a strong clue not to adopt.

The Bass model entails an important contribution to the study of innovation diffusion by modelling the process in a mathematical way. Bass (1969) proposed that potential adopters of a new innovation are influenced by two means of communication, namely mass media and word of mouth. The Bass model further assumes that there is a group of ‘innovators’, that exclusively use mass media as source of information, and ‘imitators’, that exclusively use word of mouth. Whereas the Bass model approached the market the market as an aggregate, several researchers developed micro-level models to study the individual foundations of innovation diffusion (see e.g., Mahajan et al., 1990). For example Chatterjee and Eliashberg (1990) contributed to the modelling of innovation diffusion by introducing a micro-level model that allows studying the effects of heterogeneity in populations on the diffusion of innovations. Such a micro-level model is the basis of our model of co-evolving firms and consumers.

3 The simulation model of co-evolving firms and consumers

3.1 Overview

The model is designed to analyse under which conditions green products can successfully be introduced. Green products are defined as products with an alternative design such that less physical resources are required during its life cycle. Products are implemented as a chain of actions. The non-green type of product is sold to the consumers, and will not return back to the producer. The green product is leased to the consumats, the artificial consumers in our model. In Section 3.3 we will explicate the rules that constitute this artificial consumer. Old products are taken back by the producer, which refurbish products for the production of new products (Fig. 1).

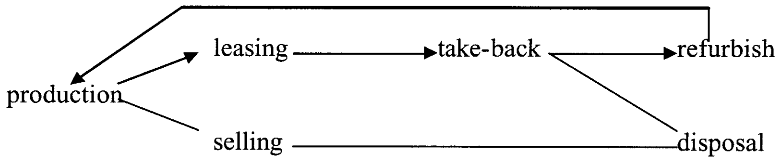

Fig. 1. Chain of actions for products, which are sold and leased. The bold line indicates the remanufacturing cycle for green products

Firms who are innovators are assumed to change their product design when they do not meet their business target, defined as a minimum average profit rate. At such events, firms may decide to introduce a green product. Adoption of green products by the consumats depends of the price, the specific characteristics of the available brands of the products, and products, consumed by the consumats' neighbours in their social network. Whereas we acknowledge the fact that some consumers strongly weight environmental outcomes in their buying behaviour, most consumers do not, and hence we do not formalise an environmental need of consciousness in the model of the consumat explicitly. Environmental motivations are, like many other motivations, included in an abstract way in the style characteristic of the product (see below).

The model consists of two submodels for the simulation of n_C consumers and n_F firms. These multi-agent models are linked with each other via a number of global equations translating product prices to product demand.

The global product demand $Q(t)$ is equal to an amount of money $M(t)$ divided by the average price $p(t)$.

$$Q(t) = \frac{M(t)}{p(t)} \tag{1}$$

The amount of money $M(t)$ which the market is inclined to spend on buying products is assumed to be equal to (Kwasnicki, 1998):

$$M(t) = M_0 \cdot e^{t \cdot g} \cdot [p(t)]^{\varepsilon} \tag{2}$$

Where M_0 is a parameter characterising the initial market size, g is the growth rate of the market and ε is the average price elasticity. The average price of all products offered for sale on the market is equal to:

$$p(t) = \sum_{i=1}^{n_F} p_i(t) \cdot \frac{Q_i^D(t)}{Q(t)} \tag{3}$$

where $Q_i^D(t)$ the demand for product i is equal to

$$Q_i^D(t) = Q(t) \cdot f_i(t) \tag{4}$$

Where$f_i(t)$ is the market share of product i. Note that we have assumed that the production offered by the firms exactly fits the demand of the consumats.

3.2 Firms

The simulation of firm behaviour is based on concepts from evolutionary economics (e.g. Nelson and Winter, 1982). Firms are assumed to have incomplete knowledge of the future behaviour of competitors. Instead of deliberating on optimal decisions, firms' behaviour is often based on routines. These routines can be seen as genotypes of the firms. Like biological evolution the compositions of these genotypes can change in time. A new routine can be discovered (mutation), or routines of competitors are imitated (recombination). The changes of routines depend on investments in R&D and whether the firms focus on imitation or innovation. Technical characteristics of the firm are functions of genotypes. The biological equivalent of these characteristics is the phenotype.

How resources are allocated to different types of research affects the technical characteristics of the firm. Whether firms will be successful on the market depends on the behaviour of the consumats. Although some products may be technically superior, consumats may decide to consume other products, as we will explain in the consumer model section. In modelling firms we crudely assume that firms measure their success in terms of the moving average of profit rates.

The models of the firms are kept very simple, since our main interest is the adoption of products by consumers. Each firm is assumed to produce one product. The production functions of the firms are all equal. Firms decide on the capital stock (investments) in order to produce the expected level of production. Firms observe the market shares and costs of the competitors. All firms take the decisions simultaneously and independently. After the investment decisions are made, the firms undertake production and put products on the market. The consumats' decision process to buy the product is described in Section 3.3. Firms can adapt their products in terms of style, the design (non-green or green) and the degree of refurbishing of a green product. Style refers to non-technical characteristics that influence the choice of the consumer, such as colour and shape. The degree of refurbishment increases in time. Such an increase occurs with a certain probability. The higher a firms' investments in R&D, the higher is the probability of improving refurbishment.

The three phenotypes are implemented as follows. The style of the product d_1 is a value between 0 and 1, the design of the product d_2 is non-green (1) or green (0), and the degree of refurbishment d_3 is a value between 0 and 1, which can only increase in time.

The design of the products can change in time. Firms are assumed to be either *imitators* or *innovators*. *Innovators* investments in R&D result in changes in the product composition, that is the style, design and refurbishment. Whether the changes in the phenotypes improve the performance of the firm depends on the decisions of the consumers. *Imitators* also invest in R&D, but at a lower level than the *innovators*. They copy the design of the firms who had the best performance during the last few years. This performance is measured by the obtained market share.

The firms are assumed to innovate or imitate only when they do not have met their long-term target of a certain profit rate. This simplistic assumption is based on satisfying behaviour of the firms. As long as they are satisfied, they do not take risks in trying out new products. The long-term profit rate is the result of previous investments and output of the firm.

Given the demand for product i, Q_i^D, is equal to production of goods Q_i, the capital inputs can be calculated:

$$Q_i = \alpha_i \cdot (K_i^j)_i^\gamma \tag{5}$$

Where K_i^j is the capital stock for producing product i, which can be a non-green product ($j = c$) or a green product ($j = g$), α_i a technology parameter, and γ represents the elasticity with respect to capital. Rewriting the production function leads to the required size of the capital stock:

$$K_i^j = \left(\frac{Q_i}{\alpha_i}\right)^{\frac{1}{\gamma}} \tag{6}$$

Taking into account that the capital stock will decrease not faster than depreciation at rate $1/L_K$, the actual size of the capital stock is then defined as:

$$K_i^j = MAX\left(K_i^j, K_i^j(t-1)\cdot\left(1-\frac{1}{L_K}\right)\right) \tag{7}$$

The price which have to be paid by the consumat is defined as a minimum price $p_{min,i}$ multiplied by a factor that takes into account the market share, a profit margin $\Phi(>1)$ and an elasticity η. The higher the market share, the higher the price that will be asked from the consumat, which represents the impact of market power of economic agents.

$$p_i = p_{\min,i} \cdot (Qd_i/Qd + \Phi)^\eta \tag{8}$$

The minimum price is defined as a cost price per unit of production. For every unit of production a unit of capital is invested in line with equation (6). The annuity rate translates capital investments into years depreciation and is defined as $a = \frac{r}{1-(1+r)^{-EL}}$, where r is the interest rate and EL the economic lifetime of the capital investment. The cost of material inputs depends on the price of material p_m and the amount of material inputs. When the product is a non-green one, $d_{2,i} = 1$. In case the product is a green design, the inputs depend on the refurability rate. Since a fraction of the output is invested in research and development ($I_{R\&D,i}$) the minimum price is increased by dividing the costs by $(1 - I_{R\&D,i})$

$$p_{\min,i} = \frac{a\cdot\left(\frac{Q_i^D}{\alpha_i}\right)^{1/\gamma} + p_m\cdot Q_i^D\cdot(d_{2,i}+(1-d_{2,i})\cdot d_{3,i})}{(1-I_{R\&D,i})\cdot Q_{ii}^D} \tag{9}$$

The returns of a firm are equal to the price p_i times the production Q_i. For the calculation of the profit of the firm, costs of R&D, capital investment and material inputs are subtracted. The costs of R&D are a fraction $I_{R\&D,i}$ of the returns. This fraction can have two values, depending on whether the firm is an innovator or an imitator. The capital investments are equal to the capital stock for both non-green and green products times the annuity factor a. The costs of material inputs are equal to a fixed material price p_m and the material inputs.

For each firm i the profit Π_i is equal to

$$\Pi_i = Q_i \cdot p_i \cdot (1 - I_{R\&D,i}) - a \cdot (K_i^c + K_i^g) - p_m \cdot Q_i \cdot (d_{2,i} + (1 - d_{2,i}) \cdot d_{3,i}) \quad (10)$$

3.3 Consumers

For the simulation of consumption we build on the model of Janssen and Jager (2001). This model simulates how psychological factors of consumers affect market dynamics. The model is based on the consumat approach (Jager, 2000). Based on a comprehensive conceptual model of consumer behaviour that offers a kind of meta-theory of human behaviour, artificial consumers, the consumats, are implemented. A number n_C of consumats consume one product on each time-step. The consumats have two needs, namely a social need and a personal need.

The personal need expresses the personal preferences or taste of a consumat for certain products. The level of need satisfaction for the personal need depends on the difference between the dimension $d_{1,j}$ of the consumed product j and the preferred characteristics by the consumat i, p_i: s

$$N_{ij}^p = 1 - |p_i - d_{1,j}| \quad (11)$$

The satisfaction of the social need is related to the sense of belongingness and the use of common symbols. As regards the consumption of products, this may be formalised as having a preference for consuming the same products as the neighbours. The more neighbours consume the same product, the higher the satisfaction of the social need. We assume that consumats prefer to consume the same as their neighbours as to stress their social identity, although other implementations of identity can be used (Janssen and Jager, 2001).

A social network, which indicates who ones neighbours are, is implemented in line with the Watts-Strogatz model (Watts and Strogatz, 1998). This model includes the empirical found characteristics of social networks, namely the small-world effect and the clustering effect (Newman, 1999). The small-world effect refers to the experience that despite a large population, the map of who knows whom is such that we are all very closely connected to one another. The cluster effect denotes the observation that people's circles of social contacts tend to overlap to a great extent. Your friend's friends are likely also to be your friends. The Watts-Strogatz model simulate these effects by building a model that is a regular lattice having some degree of randomness in it (Fig. 2).

A market share m^s can be calculated indicating how many neighbours in the social network consume the same product. The level of need-satisfaction for the social need N^s is higher the more neighbours consume the same product, and hence the level of the social need reflect the notion how many neighbors of agents i consume the same product j.

$$N_{ij}^s = m_{ij}^s \quad (12)$$

The total level of need satisfaction of consuming product j is equal to

$$N_{ij} = \beta_i \cdot N_{ij}^s + (1 - \beta_i) \cdot N_{ij}^p \quad (13)$$

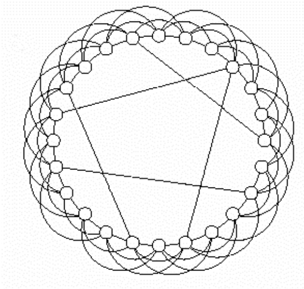

Fig. 2. A Watts-Strogatz model of social networks

Where β_i weighs the influence of the social need and the personal need. A low β_i holds that the personal need is weighted more, as is usually the case with more innovative people (Rogers, 1995), whereas a high β_i holds that the social needs are weighted more, as is usually the case with less innovative people.

Prices influence the relative satisfaction rate of an opportunity. Since higher prices reduce the expenditures in other opportunities to increase the level of need satisfaction, satisfaction levels are compared per unit of price. The need satisfaction equation (13) is rescaled by the relative price level

$$N_{ij} = \frac{\beta_i \cdot N_{ij}^s + (1 - \beta_i) \cdot N_{ij}^p}{p_j^\kappa} \tag{14}$$

where κ is a scaling parameter and p_i is the price of product j. Notice that the choice for green versus non-green products is a function of individual preferences, social needs and price levels.

Heterogeneity in our model is thus introduced at two levels. First, it pertains to individual variations considering personal preferences regarding the product characteristics. Second, it resides in different weights of the personal need against the social need. The introduction of a social need is a major extension in comparison to the modelling approach of Chatterjee and Eliashberg (1990), who only use product performance and price as determinants of heterogeneity of consumers.

In deciding what product to consume, the consumat may employ different cognitive processes. The type of social processing the consumat engages in depends on the level of need satisfaction and on the experienced uncertainty. Uncertainty U_i is defined as the squared difference between expected level of N, which is assumed to be equal to N at time $t - 1$, and the actual N:

$$U_i = \sqrt{ABS(N_i - N_i(t-1))} \tag{15}$$

Cognitive processing

The consumats may engage in different cognitive processes in deciding how to behave, depending on their level of need satisfaction and degree of uncertainty. Consumats having a low level of need satisfaction and a low degree of uncertainty are assumed to deliberate, that is: to determine the consequences of all possible decisions given a fixed time-horizon in order to maximise the level of need satisfaction. Consumats having a low level of need satisfaction and a high degree of uncertainty are assumed to socially compare. This implies the comparison of the own previous behaviour with the previous behaviour of consumats having about similar abilities, and selecting that behaviour which yields a maximal level of need satisfaction. When consumats have a high level of need satisfaction, but also a high level of uncertainty, they will imitate the behaviour of other about similar consumats. Finally, consumats having a high level of need satisfaction and a low level of uncertainty habitually repeat their previous behaviour.

The threshold parameters N_{min}, the minimum level for satisfaction, and U_T, the uncertainty tolerance level, are given. Given the values of N_i and U_i the type of cognitive processing of the consumat can be defined.

– Repetition (Satisfied and certain: $N_i \geqslant N_{min}; U_i \leqslant U_T$) The consumat continues to (habitually) consume the product that has been consumed in the previous time step.
– Deliberation (Dissatisfied and certain: $N_i < N_{min}; U_i \leqslant U_T$) The consumat will evaluate the expected N_i of each product, and will consume the product with the highest level of N_i, that is satisfaction per unit costs. When more than one product have the highest score, the choice is at random between the candidate products.
– Imitation (Satisfied and uncertain: $N_i \geqslant N_{min}; U_i > U_T$) The consumat evaluates the products that are being consumed by its neighbours. The product with the largest share among the neighbours will be chosen for current consumption. In case of more than one candidate product, the choice is at random between the candidate products.
– Social comparison (Dissatisfied and uncertain: $N_i < N_{min}; U_i > U_T$) The consumat evaluates the product that is consumed the most by its neighbours. The expected satisfaction resulting from consuming the candidate product is compared by the expected satisfaction of the product consumed in the previous time-step. The candidate product with the highest satisfaction per unit price will be chosen for consumption.

The eventual survival of products on the market depends on which products will be consumed following these cognitive processes.

In comparison to the Bass model (Bass, 1969), our model does not beforehand distinguish between a group of ‘innovators’, that exclusively use mass media as source of information, and ‘imitators’, that exclusively use word of mouth. Rather, we assume that the word of mouth is an expression of two underlying social dynamics. First of all, the cognitive processes of imitation and social comparison express the tendency of people to take their neighbours behaviour as a benchmark. Secondly, the social need expresses the tendency of people to find their neighbours consumptive behaviour attractive. Both processes operate through word of mouth, but also by observing the behaviour of others. Moreover, in our model the agents only consider new opportunities when deliberating, which can be interpreted as that the mass medial information about the availability of new opportunities is only perceived during deliberation. The difference with the Bass model is thus that we do not formalise differences between two groups regarding their innovativeness, but that we formulate innovativeness as a variable that depends on the decision making process of individual agents. In the next section we will demonstrate how this model elucidates the behavioural dynamics behind innovation diffusion.

4 Model experiments

4.1 Experimental set-up

A number of experiments have been performed to analyse how the characteristics of the agents, consumats and firms, on the rate of diffusion of the green products. In the simulation experiments we formalise 100 consumats, and 10 firms. The experimental conditions will differ regarding the product development rules, the consumat rules, and the tax policy on non-green products. Each experimental condition involves 100 model runs, with random values for the consumat preferences and initial product characteristics. The time horizon is 100 time steps, which resembles a period of a few months up to a few years, depending on the type of market.

Product development rules

Two experimental conditions are being based on the product development function of the firms. In the first condition, a fixed set of 10 products remains for the whole time horizon: 5 non-green and 5 green products. In this ‘fixed set of products’ condition, each firm produces its own product for the full simulation period, and only their market shares may change. In second condition we assume that 50% of the firms are *innovators*. Initially, all firms produce non-green products. It is essential to realise that *innovators* may develop new non-green products. Moreover, in relative stable markets they may innovate at a lower rate because firms only change the design of their product when they do not meet the moving average profit target of 10%. As a consequence, a large market share obtained by *innovators* does not automatically imply a large market share for green products.

Consumat rules

One experimental condition will set the consumats so as they exclusively engage in deliberation, thereby representing the rational actor, which we henceforth will address as *Homo economicus (HE)*. In the other experimental condition the consumats are set as to engage in all four types of cognitive processing, which we will address as *Homo psychologicus (HP)*.

Tax policy

The green products are more expensive than the non-green products which are implemented by assuming different α values (see equation (6)): $\alpha = 1$ for the green products and $\alpha = 2$ for the non-green products. This causes that an external policy is needed to generate diffusion of the green products. This is mainly since the simplistic formulation of the firms. They do not make advertisement (generating dissatisfaction), price shortcuts, or other campaigns. Furthermore, the prices do no decline due to learning, technical development and cost reductions. Therefore, a tax policy is only an option to stimulate consumats and firms to change behaviour. Two experimental conditions are based on the introduction speed of tax policy. Slow tax refers to a linear increasing tax rate (*slow* tax) from time step 25 up to a fixed level at time step 75. *Fast* tax refers to the introduction of a tax rate at once at time step 50. In both conditions the final tax-rate is 0.5, indicating about a doubling of the prices for non-green products. When most consumats are satisfied, they will not change behaviour (lock-in), and hence a tax may 'shake up the system' and stimulate consumats to consider alternative products.

Design of the study

The simulation experiments thus follow a 2 (product development rules) $*$ 2 (consumat rules) $*$ 2 (tax policy) design. In the following sections we will present the results. In the first section we will discuss all the results for the fixed set of products conditions. After that we will present the results for the product development condition. We will conclude this section with a series of sensitivity analysis.

4.2 The 'fixed products' conditions

In Figure 3 we observe the diffusion of green products for the four consumat $*$ tax conditions. In all conditions the tax rate of 0.5 appears to be sufficient to obtain a full diffusion of the green products. During the first 25 time steps, when the tax rate is zero, there is a small percentage of green consumption. This is caused by the fact that for a few consumats that heavily weigh their personal needs (equation (11)) the green product is more satisfying, despite its higher price. The level of initial green consumption is higher for the HE, because of the full deliberation of all options, compared with the satisfying behaviour of the HP. An introduction of a tax leads to a faster response by the HE, but in all cases elicits a total switch of consumption patterns after time step 60.

Fast tax

Figure 3 shows that in case of a fast tax, the HE responds immediately by switching to green products. The HP responds a bit later, and it requires about 7 time-steps for the green products to diffuse completely. Introduction of the fast tax shows first a peak in social comparison because the outcomes of their behaviour change (eliciting uncertainty) in an unwanted direction. However, because hardly any consumats consume green products, this social comparison process does not elicit a large behavioural change. This only starts when in the next time step the consumats are used to the change (reducing uncertainty), and many of them start to deliberate about more attractive alternatives. The resulting shift in consumption again stimulates consumats to engage in social comparison, but now many consumats already consume the green product, and thus the diffusion completes. Because the green products are more expensive than the (untaxed) non-green products, the consumats will not be that satisfied, and hence they engage in reasoned processing (deliberation or social comparison) after the transition has been completed.

Slow tax

Figure 3 shows that the slow tax also leads to a slower diffusion of the green products in comparison to the fast tax condition. Moreover, we observe that also in the slow tax condition the HP adopts the green products at a slower rate than the HE. This is caused by the fact that the HE deliberates on every time-step and thus reacts to the new tax regime, whereas the HP may engage in repetition, or imitate the behaviour of an imitating other.

This causes that the HP may be not aware of the changing tax, or socially compares whilst the social network in majority consumes non-green products. Hence the HP does not immediately react to the changing tax. In the slow tax condition, the HP shows a smooth transition of cognitive processes.

Whereas the tax increases linearly, the population of HP that uses a green product shows a typical S-shaped diffusion graph. This effect is due to the effect of the social need and heterogeneity of the weight of needs. When some deliberating

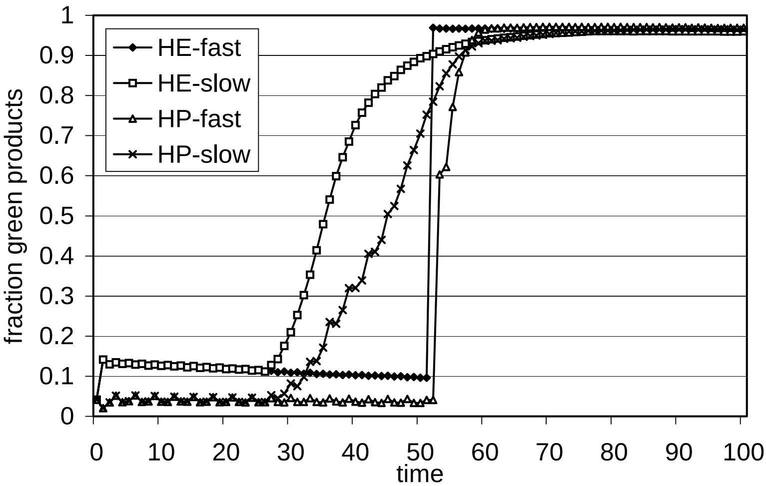

Fig. 3. Diffusion of green consumption when there is a fixed set of products

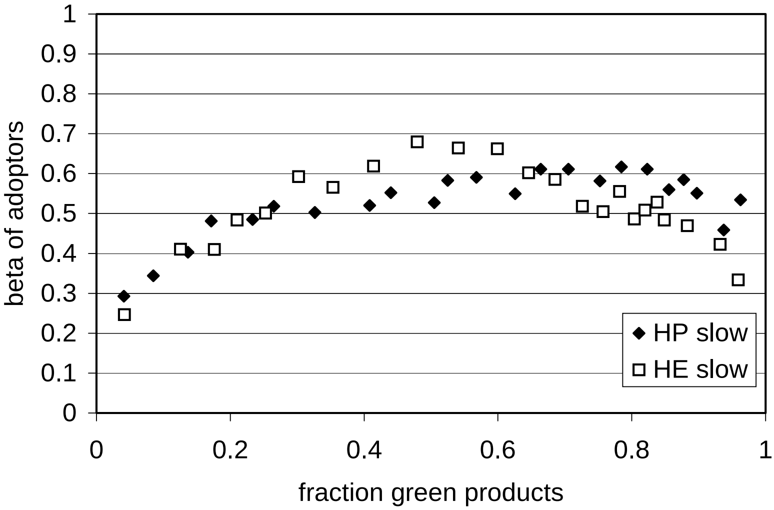

Fig. 4. The relation between the value of beta and the moment of changing to green consumption. For both the HP as well as the HE the consumats who weight social need more than the personal need

consumat start consuming green products because it better satisfies their strong personal need, this affects the social network of the consumats. Hence, other consumats may subsequently expect a higher social need satisfaction following green consumption. This shows that the transition process accelerates when a critical number of consumats have adopted green products. Especially the consumats with a strong social need will change their consumption during this rapid transition. At the end of the transition we observe that the speed is decelerating, which is caused by the consumats with strong personal needs that do not appreciate the green products very much, but which are forced by the increasing tax. This observation of the importance of heterogeneity in the weighting of the social versus the personal need is confirmed when we look at the average value of β of those agents who shift from non-green to green products projected against the fraction of consumats that already shifted to green products (Fig. 4).

This figure shows that the early adopters have a low β value, thus weighing their personal needs more. During the middle part of the transition, the β values of the switching agents are higher, illustrating the higher weighing of the social need. These results are in line with the empirical observation of Rogers (1995). However, for the late adopters and laggards we observe a slightly lower β value for the HP and a much lower β value for the HE. This suggests that the late adopters and laggards pay less attention to the social need as is suggested by Rogers. However, these agents may be forced to switch towards green consumption because (1) the price of the non-green product has risen that far that it outweighs the consumats preference for a non-green product, and (2) their social need has been depleted that much that it pays to switch towards the green product all their neighbours are consuming.

If we look at the consequences for the material input, we observe that these follow a similar behaviour as the diffusion process (Fig. 5). The default trend of

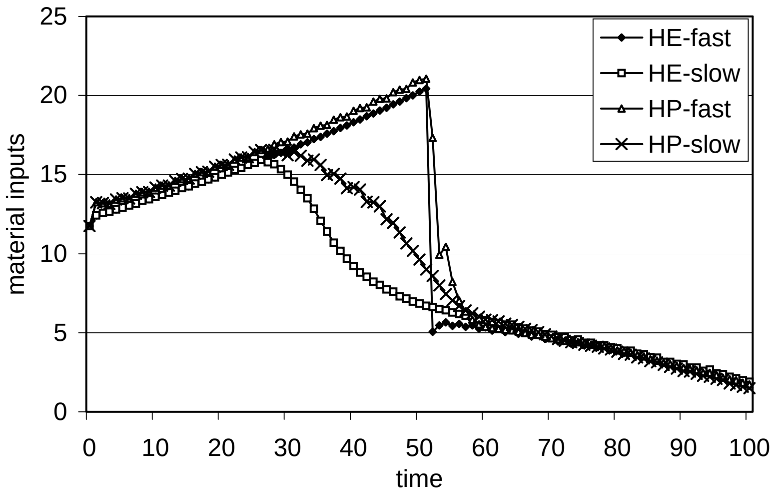

Fig. 5. Material inputs when there is a fixed set of products

material inputs is a gradual increase due to an external growth rate of the economy (Eq. (2)). The absolute size of material inputs is determined by the total consumption, the type of consumption and the posibility to refurbish green products. The absolute amount of consumption decreases when the prices increase (see Eq. (1)). The type of production is determined by the diffusion of green production. The ability to refurbish green products increase in time due to investments in R&D. The combination of the factors lead to a reducing level of material inputs after the tax intervention. The dominant factor is therefore the improvement of the ability to refurbish after the switch to green products.

4.3 The 'development of products' conditions

In the 'development of products' condition we start initially with no green products on the market. Innovative firms thus need to switch to developing green products to make a transition possible. This leads to a delay of the diffusion processes as illustrated in Figure 6. Whereas in the previous condition the strongest effect was found for the rate of the tax introduction, here the main effect discriminates between the cognitive rules the consumats employ. We observe that for the HP the diffusion reaches a level of 80 to 90% at $t = 100$, whereas the HE reaches a level of about 30 to 40%. Furthermore, the gradual increase of tax introduction results in a lower diffusion rate compared with a fast tax introduction. Before we explain the differences due to the speed of tax introduction, we will have a closer look why the HE leads to a lower diffusion rate.

The main explanation of a faster diffusion when consumats are HP resides in the fact that the variability in market shares is much larger under the HP condition. This is being caused by the fact that social comparison and imitation may cause consumats to consume the same product as other consumats, despite the often

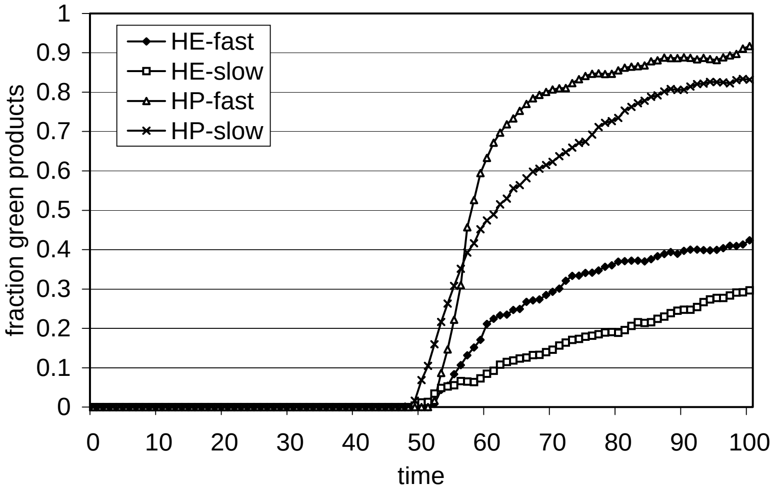

Fig. 6. Diffusion of green consumption when firms change the design of their products

lower outcomes associated which that behaviour. These dynamics may cause one product to obtain a large market share, at the cost of others. Firms with very small market shares may not meet their profit targets and start to innovate or imitate. The dynamics of product renewal are thus faster and more frequent in the HP conditions. These dynamics stimulate an earlier introduction of green products, and consequently, consumats in the HP conditions start earlier with green consumption. Under condition of renewal of products it appears that cognitive processes such as imitation and social comparison accelerate the diffusion process.

The innovative firms derive a larger market share in case of the HP experiments (Fig. 7). Being the first on a market with an interesting green alternative provides the chance of being adopted by a large share of the population due to social comparison and imitation processes.

Both for the HE as for the HP we observe that a slow tax leads to a slower diffusion than a fast tax (Fig. 6). In the slow tax conditions we observe that green products enter the market just before $t = 50$, at what point the tax is almost halfway its linear increasing path (tax level is about 0.25). In the fast tax the green products enter the market after $t = 50$, at what time the tax of 0.5 is imposed on the non-green products. The question is why a fast tax stimulates diffusion, even after time step 75, where in both conditions the tax remains at a stable level of 0.5? The answer resides in the co-evolutionary dynamics. In case of a fast tax the profits for firms drop rapidly due to a decrease in demand. As a consequence, many firms do not meet their profit targets and start redesigning their products, including the introduction of green products. In case of a gradual tax introduction, firms have more time to adjust to changed conditions (e.g. production capacity). Therefore, a fast tax is more capable of shocking the system, thereby stimulating a transition towards the production and consumption of green products. For the HP experiments there is an additional factor. A tax shock leads to dissatisfaction of many consumats, resulting in exploring new products in case of deliberation. Also social comparison

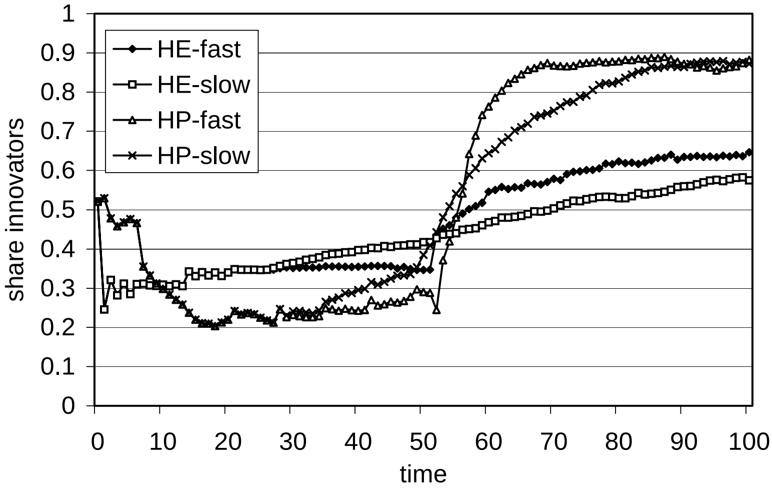

Fig. 7. Share of consumed products which are produced by innovative firms

is more frequently being employed, which in this case accelerates the diffusion of green products. A gradual introduction of a tax shows a slower increase in the proportion of deliberation, starting at about $t = 30$ when the tax rise makes more and more consumats dissatisfied. Many consumats remain repeating their previous behaviour, which of course slows down the diffusion process.

These results suggest that a fast tax stimulates a faster transition, which causes the consumats to experience a higher level of need satisfaction in the long run. Because at the point of introduction of the fast tax the consumats are less satisfied than at any point in the slow tax condition, here the saying 'no pain, no gain' appropriately summarises the rationale of the fast tax policy.

In the experiments where firms can develop new products we do not observe that the early adopters relatively weigh more their individual needs (low β), and later adopters their social needs (high β) (Fig. 8), as observed by Rogers (1995) and as observed in the experimental conditions with fixed products (Fig. 4). On the contrary, we observe that the consumats with the lowest β usually adopt later to the green products. This has to do with the co-evolutionary processes that cause firms developing products in the pre-tax period that very well fit to the individual needs of the consumats. When firms are able to adapt their product, consumats use a much higher proportion of repetition, indicating a higher satisfaction level. Especially the consumats with a low β will experience a higher satisfaction than the consumats with a high β, because the products fit their individual needs. The consumats with a high β on the contrary are often less satisfied because the continuous product development causes that the other consumats in their social network more often switch from product, and hence their social need is often less satisfied. Because of their lower satisfaction, they are more likely to deliberate about alternative products, and hence they may be the first to perceive the relative attractiveness of the green products due to the changing tax regime. The satisfied consumats with a low β are more likely to persist in their habitual behaviour, and consequently they are often

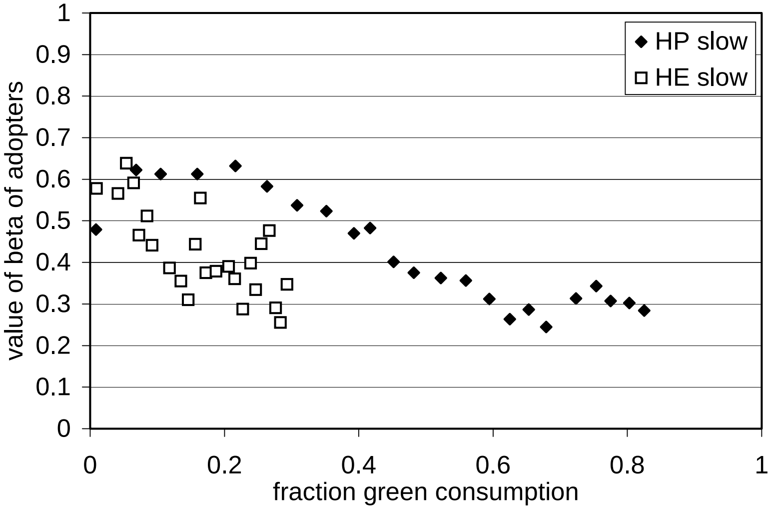

Fig. 8. The relation between the value of beta and the moment of changing to green consumption when firms can change the design of their products

the latest to change their behaviour. Sometimes they are forced to change when their favourite product is not produced anymore. These results suggest that the characteristics of the people that innovate depend on the type of market they operate in. Many markets that have been studied in the context of innovation diffusion can be described as slowly renewing, such as agricultural practices, contraceptives and health related behaviours. Here the innovators are more likely people that attach greater value to their individual needs. On the basis of the simulation results we expect that the same people are more frequently late adopters in less stable markets with repetitive consumption. Examples of such markets are fashion, home decoration and cellular phones.

When we observe the consequences for the material inputs, we observe that the growth of material inputs decreases when the slow tax is imposed (Fig. 9). This is due to the higher prices that decrease consumption. However, the largest difference can be seen after the introduction of the fast tax. Here we see a decrease in the material inputs. However, after a few time steps we observe that the material inputs for both HE conditions rise, and for both HP conditions decrease to a lower stable level. This clearly reflects the successful innovation diffusion for both HP conditions.

4.4 Sensitivity analysis

Sensitivity to the tax level

Using the model version of fast responding firms, we explored the diffusion rate after 100 time steps of simulation for various tax levels Figs. 10). When the tax level is lower than 0.3, there is no diffusion of green products. The only implication of the

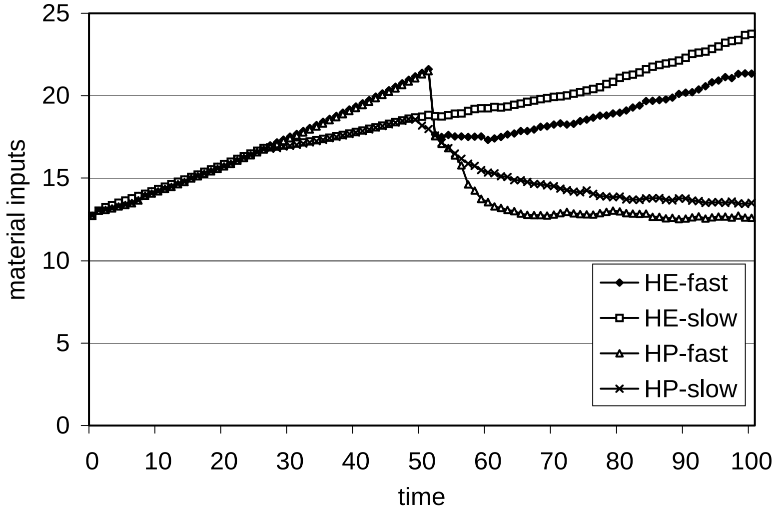

Fig. 9. Material inputs when firms change the design of their products

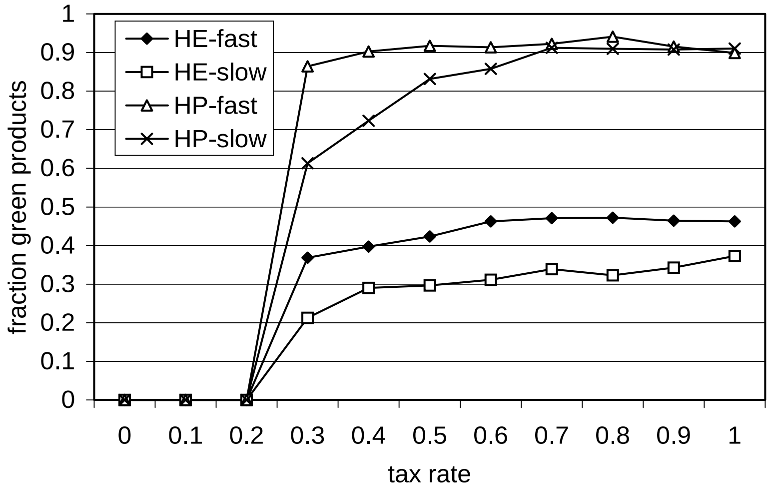

Fig. 10. Fraction of green products after 100 time steps for different tax rates

tax, is the reduction of the demand. Those tax levels seem to be too low to provide firms enough prospects to shift to green products. At higher tax levels the order of impact between the tax policies and implementations of cognitive processes of the consumats remain the same as observed with a tax level of 0.5 in the default case. We only observe a convergence of the impact of fast and slow introductions of tax policies at high tax levels when the consumats are HP.

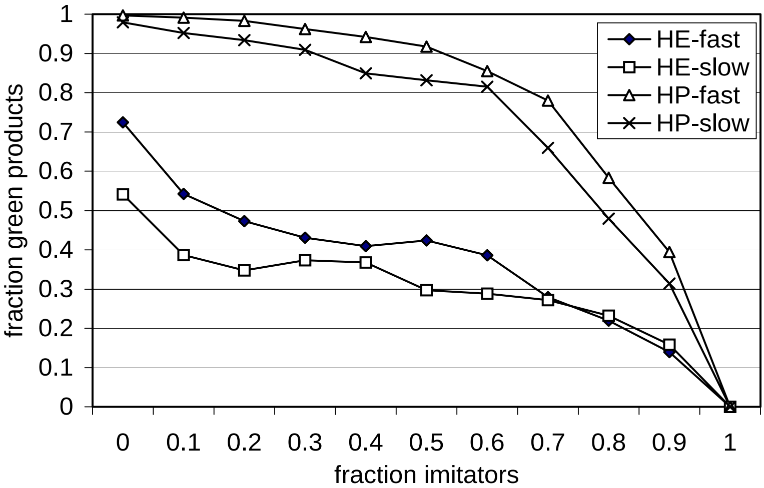

Fig. 11. Diffusion of green products after 100 times steps for different fractions of imitators among the firms

Imitators versus innovators

Not only the characteristics of the consumats determine the success of diffusion, also the characteristics of firms are important. In the next analysis we use the model version with fast responding firms, and we vary the proportions of innovating versus imitating firms. The distribution of imitators versus innovators clearly determines the degree of diffusion Fig. 11). For different settings of consumat characteristics, an increase of 0% imitators to 60% imitators has moderate impact on the decrease of the level of diffusion. Beyond this point the decrease of diffusion is large, and drops to zero when all firms are imitators.

5 Conclusions

The two formulations of firms we used in these model-based experiments are extremes. Either the firms offer 1 product that is never being changed, or the firms are extremely adaptive, willing and able to change their product immediate if neccesary. Clearly, firms in the real world will display more complex strategies that are more positioned between the extremes as formalised in this paper. However, despite this simplicity in the modelling of the firms, the experiments yield some interesting conclusions from the perspective of consumer behaviour. First, the results suggest that more deliberation, as is usually the case with important consumptive decisions, yields a faster diffusion in a market where firms do not adapt there products, but a slower and not complete diffusion in a market where firms continuously adapt their product designs. Moreover, it appears that in both markets different types of consumats function as innovators and early adopters. The results also suggest that the introduction speed of tax policy is more important when firms do not adapt versus the case where firms adapt their product design. Whereas the results for the fixed portfolio of products correspond to the results as reported by Rogers (1995), the results for the case where firms adapt their products designs show a different perspective. For example, we observed that the consumats that attached more weight to their social needs were amongst the innovators and early adapters, which contrasts with the results of Rogers (1995). Empirical research that is focussing on the innovation diffusion process in markets with rapid adjustment of product designs should be performed to confirm this hypothesis.

Green technology is being applied in various types of markets, which differ regarding speed of renewal and the dominating decision processes. For example, we may distinguish between markets with high importance of social compatibility, but low decision importance (e.g., clothing), low importance of social compatibility and low decision importance (e.g, foods), high importance of social compatibility and high decision importance (e.g., cars, solar power) and low importance of social compatibility and high decision importance (e.g., heating devices, expensive household appliances). These markets will differ regarding their market dynamics, and thus we assume that the producers in these markets differ regarding their adaptability. Hence, we expect that stimulating the diffusion of green products in these different markets should focus on different types of consumers. Moreover, it may be expected that different policy options appear to be most effective in addressing different groups of consumers.

The simulation experiments of co-evolving consumer and firm behaviour led to interesting insights and predictions of empirical phenomena. We hope that they will stimulate additional empirical and conceptual work on this important topic.

References

Arthur WB (1989) Competing technologies, increasing returns and lock-in by historical events. The Economic Journal 99: 116–131

Bass FM (1969) A new product growth model for consumer durables. Management Science 15: 215–227

Boons FA (1998) Caught in the Web: The dual nature of networks and its consequences. Business Strategy and the Environment 7: 204–212

Boons FA, Baas LW (1997) Types of industrial ecology: the problem of coordination. Journal of Cleaner Production 5: 79–86

Chatterjee R, Eliashberg J (1990) The innovation diffusion process in a heterogeneous population: a micromodeling approach. Management Science 36 (9): 1057–1079

David PA (1985) Clio and the economic of QWERTY. American Economic Review 75 (2): 332–337

Ehrenfeld JR (1997) Industrial ecology: a framework for product and process design. Journal of Cleaner Production 5 (1–2): 87–95

Gross N (1942) The diffusion of a culture trait in two Iowa townships. M.S. Thesis, Ames, Iowa State College

Jager W (2000) Modeling consumer behaviour, PhD thesis, University of Groningen

Janssen MA, Jager W (2001) Adoption of new products in a market of changing preferences and social networks. Journal of Economic Psychology 22: 745–772

Kwasnicki W (1998) Skewed distributions of firm sizes – an evolutionary perspective. Structural Change and Economic Dynamics 9: 135–158

Liebowitz SJ, Margolis SE (1999) Winners, losers and microsoft. The Independent Institute, Oakland, CA

Mahajan V, Muller E, Bass FM (1990) New product diffusion models in marketing: a review and directions for research. Journal of Marketing 54: 1–26

Moore GA (1991) Crossing the chasm: marketing and selling high-tech products to mainstream customers. Harper Collins, New York

Nelson RR, Winter S (1982) an evolutionary theory of economic change. Harvard University Press, Cambridge, MA

Newman MEJ (1999) Small worlds – the structure of social networks, Santa Fe Institute working paper, 99–12–080, Santa Fe, NM

Rogers EM (1962) Diffusion of innovations. The Free Press, New York

Rogers EM (1995) Diffusion of innovations, 4th edn. The Free Press, London

Rogers EM, Daly H, Wu T (1980) The diffusion of personal computers. Stanford, CA, Stanford University, Institute for Communication Research, Report

Ryan B (1948) A study in technological diffusion. Rural Sociology 13: 273–285

Shapiro C, Varian HR (1999) Information rules. Harvard Business School Press, Boston, MA

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

Steg L, Tertoolen G (1999) Affective motives for car use. In: PTRC, transport policy, planning and practice, pp 13–27. PTRC, London

Stradling GS, Meadows ML, Beatty S (1999) Factors affecting car use choices. Napier University, Transport Research Institute, Edingburgh

Watts DJ, Strogatz SH (1998) Collective dynamics of “small-world” networks. Nature 393: 440–442