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**The dynamics of environmental innovations :
three stylised trajectories of clean technology**

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La dynamique des innovations environnementales : trois trajectoires stylisées de technologie propre

Résumé

Nous explorons, à l'aide d'un modèle de micro-simulation de la dynamique industrielle, la dynamique des innovations environnementales que les firmes développent pour se mettre en conformité avec la réglementation environnementale. Comment des firmes en concurrence sur un marché font face à la contrainte environnementale sans détériorer leur efficacité productive ni les performances de leur produit ? Nous nous intéressons aux technologies propres dont l'objectif est de combiner les dimensions environnementale et productive grâce aux compensations par l'innovation ("innovation offsets"). Les résultats des simulations montrent qu'une stratégie d'innovation basée sur un certain équilibre entre les dimensions environnementale et productive prend plus de temps pour porter ses fruits et elle doit faire face à un effet de destruction de compétences. Finalement, nous étudions les conditions favorables au développement de ce type de technologie propre et nous en soulignons les implications en termes de politiques publiques.

Mots-clé : *Innovations environnementales; Technologies propres; Innovation offsets; Dynamique Industrielle*

The dynamics of environmental innovations : three stylised trajectories of clean technology

Abstract

We explore the dynamics of environmental innovations developed by firms in order to comply with environmental regulations on the basis of a micro-simulation model of industrial dynamics. How do the firms competing in the same industry cope with the environmental dimension without altering their productive efficiency nor the performances of the product? We focus on clean technology which aims at combining environmental and productive dimensions thanks to innovation offsets. The results of our simulations show that an innovative strategy based on a good balancing between environmental and productive dimensions takes more time to develop and needs to face with a competence destroying effect. Finally we study the favourable conditions to the development of this type of clean technology and we draw some policy implications.

Keywords: *Environmental innovations; Clean technologies; Innovation offsets; Industrial dynamics*

JEL : O32 - Q2

Introduction

Today technological change is considered as playing a positive role to reduce polluting emissions and to cope with environmental constraints (Fukusaku, 2000). Environmental regulation is necessary to stimulate new directions of search and new technological solutions. Clean technology is the most promising way of dealing with pollution since they enable to reduce pollution at source instead of treating the pollution once it has been created (Faucheux and Nicolai, 1998). However clean technology generally implies a modification of the production process and so affects the productive efficiency and the performances of the product. The difficulty for firms is linked to their ability to develop environmental innovations that combine several dimensions influencing their competitiveness. We explore this point on the basis of a micro-simulation model of industrial dynamics.

Our contribution is to propose a framework dedicated to clean technology in which we can differentiate between various types of innovative strategy according to the way firms cope with environmental and productive constraints. We take into account the opportunity for firms to compensate the costs resulting from the compliance with environmental regulation by the gains deriving from environmental innovations (cf. Porter). The model we are developing attempts to formalise the verbal argument about the major dimensions explaining the particular pattern of evolution of clean technology. Furthermore our model incorporates the main stylised facts of technological change put forth by authors of evolutionary approaches. The logic underlying the dynamic of the system involves non linear dynamics, that is the reason why our model takes the form of a simulation model. This framework enables us to study the interactions between the innovative strategy of firms in clean technology and their competitiveness. In this perspective, we try to understand how an industry could cope with improvements in environmental performances. Another part of the analysis consists in drawing policy implications. The paper is organised as follows. In section I, we present the framework for the analysis of clean technologies. In section II, we discuss the specificity of models of industrial dynamics and we present the model of clean technology. In section III, we examine what the model can tell us about the role of the distribution of environmental and productive constraints and its capacity to account for policy implications.

I. Clean technology as a trajectory guided by environmental innovations

This section is dedicated to the presentation of our framework for the analysis of clean technology. Technological change plays a decisive role in solving environmental problems through several dimensions such as control, measure, detection, cleaning and recycling. This process of change is based on what we call environmental innovations, which can be defined as combinations of competencies, knowledge, equipment and organisations required to fulfil some environmental objectives and regulations, as well as to produce new technological artefacts¹. These innovations are conducive to what Porter and van der Linde (1995) call "innovation offsets" which may compensate the costs of complying with environmental standards.

¹ This definition is based on the definition of technology given by Metcalfe (1994).

1.1 A definition of clean technology

In the field of environmental innovations, it is now usual to oppose different types of technologies according to their impact on the environment. The basic distinction is between end of pipe technology and clean technology. In the first case, the solution to the pollution problem consists in treating the pollution by the way of several technical apparatus which take effect at the end of the production process. The production process is not modified and so the level of gross polluting emissions remains the same. But these emissions are treated at the very end of the process which enables to decrease the level of final or net polluting emissions². Basic examples are filters, dust removal techniques or desulphurization equipment.

Clean technologies are linked to another type of environmental innovations which imply an integrated change in the production process. The definition of clean technology is much debated since no technology permits "zero pollution". The idea of clean technology must not be understood as a total reduction of pollution, but as a cleaner way of producing (in comparison with the existing one), which is based on an integrated adaptation and change in the production process. The crucial argument to differentiate between end of pipe technology and clean one is that the latter involves a reduction of the pollution *at source*, and thus a decrease in gross polluting emissions.

Thus in the general sense, clean technology encompasses all techniques, processes and products that avoid or diminish at source environmental damage and/or the usage of raw materials, natural resources and energy (Kemp et al., 1992). We may distinguish between four options in the way of dealing with clean technology:

Input substitution and savings: the global process of production is unchanged, but adapted to use less inputs or new less polluting ones. Examples are the replacement of CFCs by other substances, or the switch of high sulphur coal to coal with a lower sulphur content.

Pollution control and prevention technologies: the purpose is to integrate within the production process a new technology which avoids or treats polluting emissions. An example could be a new technique for paint application which allows a reduction of fumes and also paint usage. So these technologies are often linked to the first type, since they entail not only a reduction of pollution, but also input savings.

In-process recycling: this option is based on an integrated process of recovery, recycling or regeneration of waste and materials, which is conducive to a decrease in gross polluting emissions: for instance, techniques of recovery and regeneration of chlorinated solvents.

Radically new cleaner production process: in this last case, the firm completely modifies its production process and adopts a new cleaner process which generally implies radical innovations. We can give as an example the case of the firms which develop, because of regulation, new coating techniques based on water-based solutions in order to replace chlorinated solvents.

² The distinction between gross and net polluting emissions corresponds, for the former to the emissions at source or inherent to the production process, and for the latter, to the final level of emissions at the end of the production line, after the stage of treatment of gross emissions. This distinction is useful to make the difference between the pollution concerned by clean technology and the one concerned by end of pipe technology: only clean technology deals with gross emissions.

We argue that the main difficulties in the development of clean technology is linked to the need of combining several objectives: environmental goals, productive efficiency and performances of the products. As a matter of fact, a firm will accept to carry out a project of clean technology only if there is a private incentive in terms of productivity and competitiveness. This is what Porter and van der Linde (1995) call "innovation offsets", which can lower the net costs of meeting environmental regulations and lead to absolute competitive advantage for firms. According to Porter and van der Linde, innovation offsets can be divided into process offsets, linked to higher productivity, and product offsets, that is better performing or higher quality products. These arguments emphasise the multidimensional aspect of clean technology. We can argue that the development of clean technology depends on the ability of firms to cope with these several dimensions. It is the reason why we propose to apprehend clean technology as a trajectory in a multidimensional technological space.

1.2 Three stylised trajectories of clean technology

In this section, we propose a conceptual framework for the analysis of clean technology which is illustrated by case studies mainly based on ADEME³ (1998). The purpose is to show that, according to their ability to combine environmental and productive goals, firms may follow different trajectories of clean technology. We identify three stylised trajectories which are exemplified by different environmental innovations linked to the regulation of volatile organic compounds (VOCs). The case of the regulation of the emissions of VOCs is interesting since it concerns a lot of industrial sectors and triggers many research and innovative activities.

The first step in the regulation process of VOCs has been the European Directive (1999/13/CE, 11 March 1999) on "The reduction of the emissions of VOCs due to the use of organic solvents in some industrial activities and plants". The purpose of this directive is to decrease by 57% the emissions of VOCs during the period [1990-2010]⁴. The directive sets specific target values of VOCs emissions according to industrial activities. In order to comply with these target values, firms have to call into question their production process and to find a way of decreasing their emissions or a way of using solvents substitutes. We can observe two alternative ways of compliance with this regulation: either firms find new technologies or adapt the existing one in order to decrease the level of their emissions of VOCs, or firms implement a new technology with no use of solvent which allows zero VOCs emissions. In this last case, we can say that firms change paradigm: from the solvent paradigm to a new paradigm without any solvent⁵.

We can argue that according to their innovative strategy, firms follow different trajectories of clean technology. We propose to represent these trajectories in a two dimensions space which summarises the two objectives of the firms developing clean technology, i.e. environmental standards and productive efficiency. We consider two variables:

³ ADEME is the French Agency for Environment and Energy Management.

⁴ This directive concerns more than 400000 firms and 22 sectors, since many industrial activities require the use of organic solvents. The main industrial activities concerned are: treatment of surfaces, like cleaning or metal degreasing, painting, printing, dry cleaning, manufacture of automobiles, pharmaceutical and chemical activities, treatment of wood, application of glues and adhesives.

⁵ For instance in painting, the change from solvent paints to "green paints" such as water-based or powder paints.

An indicator of gross environmental performances (I_p): This indicator is decreasing with gross emissions of VOCs and represents the environmental quality of the production process of firms. We refer to gross emissions since we deal only with clean technology, and not with end of pipe technology (c.f. §I.1).

An indicator of productive efficiency (A_p): This variable summarises the efficiency of the production process which depends on many factors, such as the use of resources and materials, energy consumption, waste disposal and treatment costs, handling and maintenance costs, workplace conditions, production time and process yields.

Increases in the productive efficiency are due to what Porter and van der Linde (1995) call process innovation offsets. We distinguish between two levels of process innovation offsets: resources and energy savings -i.e. material and resources savings, lower energy consumption and reduction in waste treatment costs - and higher gains in productive efficiency due to a decrease in handling costs, shorter production time and higher process yields. Our purpose is to analyse how do firms cope with these two dimensions (I_p and A_p).

Figure 1: Three stylised trajectories of clean technology linked to VOCs emissions

Figure 1 presents three stylised trajectories of clean technology which illustrate three types of process innovation offsets associated to the regulation of VOCs emissions. We argue that these trajectories are guided by specific innovative strategy of firms. The first trajectory along the horizontal axis is called the productive strategy, since it is focused on the productive efficiency, while the most vertical trajectory is called the environmental one, and the last one is defined as the median strategy. Each strategy is exemplified with innovations linked to VOCs emissions. The threshold value of gross environmental performances $I_p^{\max 1}$ stands for

the frontier of the solvent paradigm: in order to reach environmental performances superior to this critical value, firms have to change paradigm and adopt new ways of producing with no use of chlorinated solvents.

1. The productive strategy:

This strategy leads to an increase in the productive efficiency, while the gross environmental performances index remains unchanged. The first example is the case of *energy recovering of VOCs* (ADEME, 1998). It is the case of a firm using chlorinated solvents to treat surfaces before painting. This firm sets up a new equipment consisting in a hood placed over the vat of solvents in order to capture VOCs, which are then reused for combustion in burners used to heat the baths of treatment and the oven of paints cook. Through this innovation, the firm managed to decrease its level of net VOCs emissions (because of the hood) and to increase its productive efficiency because of important energy savings. The level of gross VOCs emissions is unchanged since the firm goes on using the same chlorinated solvent for its treatment of surfaces. But it is considered by ADEME as a clean technology because the installation is integrated in the whole process and makes the junction between the treatment of surfaces and the stage of heating of baths. This technology can be conducive to significant energy savings when there is a need of heat which is closed to the source of VOCs emissions.

The second example is a combination of technologies for the recovering of VOCs and the regeneration of solvents. Because it is the most economical way to recover VOCs from a wide range of gas streams, *adsorption* is by far the most widespread technology for VOCs recovery. The principle is to put the VOC-containing gas stream in contact with a fixed bed of granular activated carbon. The VOC is adsorbed from the gas stream and the clean gas leaves the sorbent bed. Then firms use a *distillation* process to purify and regenerate recovered solvents. This combination of adsorption and distillation technologies is broadly used in the metallurgical industry. It is a way of complying with regulation by an integrated treatment of gross VOCs emissions, which decreases net emissions, while benefiting from resources savings due to internal recycling.

These two examples characterise a trajectory of clean technology based on technologies of control and prevention of pollution as well as internal recycling. Chlorinated solvents are still used as inputs for the treatment of surfaces and so the level of gross VOCs emissions remains approximately the same. In that case innovations offsets mainly come from resources and energy savings.

2. The environmental strategy:

This second innovative strategy focuses on the indicator of gross environmental performances. We give two examples of environment-friendly innovations which allow an important increase in environmental performances associated to a very low increase in productive efficiency.

The first example concerns new *techniques of paint spray* which improve the paint's transfer efficiency subsequently by allowing not only the reduction of fumes but also paint usage. Firms use the same chlorinated paints, but an improvement in the technique of application enables to decrease gross VOCs emissions. This innovation is also associated to a slight increase in the productive efficiency since there is less waste in the use of paints.

The second case is an example of a radical change in the production process which implies to give up the treatment of surfaces using chlorinated solvents to adopt a new technology which is *thermal scrubbing with fluidised bed combustors*. This example is given in ADEME (1998) and concerns a firm that changed completely its process of scrubbing by investing in a new equipment, consisting in burners and a vat with a fluidised bed of particles, which cleans the components by thermal decomposition. With this new installation, the firm decreases to zero its consumption of chlorinated solvents, makes important energy and materials savings and reduces its waste treatment costs. This is a typical example of a radical environmental innovation which allows to reach the new green paradigm without solvent, but which is not associated with significant gains in productivity. This also means that, along this trajectory of clean technology, process innovation offsets are smaller than along both other trajectories.

3. The median strategy:

This strategy is the one that combines the most efficiently the two dimensions of clean technology. The considered trajectory of clean technology is characterised by significant increases in gross environmental performances and in productive efficiency. We argue that this type of strategy is generally based on radical innovations which lead firms to implement a radically new production process. In the case of VOCs emissions, our argument is that, in order to make significant gains in productivity and in environmental performances, firms have to leave the solvent paradigm and to adopt a new production process without solvent. We propose two examples of this kind of clean technology.

The first example concerns *treatment of surfaces with low temperature plasma*. This technology mainly concerns the treatment of surfaces before application of glues, which is generally made with chlorinated solvents. The treatment by low temperature plasma uses low pressure gas that are non-polluting. This technology is still in its development stage, but some experimentations have shown that it provides a very interesting potential of application. As an example, we can present the case of a firm (SNPE, Saint-Medard) which has set up in 1998 an industrial platform of treatment of surfaces by low temperature plasma. With this new technology, the firm has carried out important gains in productivity linked to an increase in the quality and in the speed of treatments, and also to a decrease in the costs of waste treatment and in the number of operations in the treatment of surfaces. In the meantime, this new technology allows zero VOCs emissions.

The second example is given in ADEME (1998) and concerns a firm that is producing printed packaging by heliography. This firm was using chlorinated inks and alcohols which generated aqueous and gaseous pollutions. This firm completely changed its production process by substituting *water-based inks* for chlorinated ones and by suppressing alcohols. The transition to water-based inks led to several innovations, in particular new printing cylinders and a new range of water-based inks with the same quality of printing. It took to the firm three years of R&D to finalise this new technology, with a time for return on investment approximately equal to three years. Finally the adoption of the new technology resulted in a significant decrease in gross VOCs emissions, a decrease in aqueous polluting emissions, important materials savings, a diminution in the costs of waste treatment, an increase in productivity and a significant improvement in the brand image (the first heliography printer using a total water-based technology). As a conclusion for this firm, the transition to a new water-based paradigm has been a source of major innovation offsets and of competitive advantage.

These two examples illustrate what we call the median trajectory in clean technology which is characterised by simultaneous gains in environmental performances and in productive efficiency. To a certain extent, we can argue that this type of trajectory is the most interesting for firms. But these examples also show that it involves a change of paradigm, which calls for R&D investments and the implementation of a radically new production process. The example of treatment of surfaces by plasma also suggests that this type of trajectory is often based on technologies that are still in their experimentation or development stage, which implies uncertainty, high R&D investments and so some reluctance from firms. But in the meantime, it is the only trajectory which provides real gains in productivity (in terms of production time and process yields) and competitive advantage.

1.3 The evolution of the performances of the product

Generally the changes in the production process also involve modifications in the product. The main question is to determine how the performances of the product are affected by the adoption of clean technology. On this point, Porter and van der Linde (1995) insist on what they call product offsets, that occur "when environmental regulation produces not just less pollution, but also creates better-performing or higher-quality products". They present several sources of product offsets such as safer products, lower product costs (for instance from material substitution or less packaging) and products with higher resale or scrap value. Porter and van der Linde (1995) give examples of product offsets characterised by increases in the quality or by new product design for better recyclability and easier assembly.

In the case of VOCs regulation, the question of the evolution of the performances of the products is more questionable. In some cases, the transition to the paradigm without solvent is slowed down because of some difficulties concerning the quality of the product. For example, the adoption of water-based materials instead of chlorinated solvents is often associated to finishing problems. In the case of the manufacture of automobiles, some tests have been made with water-based glues for the sticking of anti-vibratory rubber components. The tests show that there is a decrease of 40% in the lifetime of the components. For this reason, firms go on using chlorinated glues.

Another example concerns metal degreasing or scrubbing in aircraft construction. The adoption of a new technology of treatment of metal surfaces, for instance low temperature plasma, calls into question the technical and safety characteristics of the products. Firms have to "re-qualify" their process to show that with this new technology the product still complies with the requested technical specifications. This is costly for firms and, in certain cases, some technical performances or safety conditions are difficult to fulfil with the new technology.

These examples show that product offsets are not systematic. We argue that they are particularly questionable when there is a change of paradigm, that is when firms radically change their production process to comply with environmental regulation. In that case, the change of paradigm may be conducive to a destroying competence effect which can decrease the performances of the product⁶. This effect is generally transitory, the time for firms to acquire the necessary knowledge and capabilities in order to adapt the performances of the products. Finally the characteristics of the product will be the third variable to be considered in firms' innovative strategy in clean technology.

⁶ This destroying competence effect is well-known in the literature on innovation and is often associated to the process of Schumpeterian creative destruction.

II. A simulation model of clean technology

In this section, we present a micro-simulation model which enables us to depict the different trajectories of clean technology and their influence upon the evolution of industrial structures. Our purpose is to give to the three stylised trajectories of clean technology some micro-foundations in terms of R&D activities of firms. The model is proposed as an exploratory framework for a dynamic analysis of clean technology based on innovative activities of firms.

II.1 The modelling of industrial dynamics

The purpose of the model is to study the impact of the activities of innovation in clean technology upon the evolution of the industrial structure. In order to tackle this question, we propose to use a micro-simulation model of industrial dynamics which is inspired by evolutionary modelling. A model of industrial dynamics is dedicated to the analysis of the co-evolution of the technology of firms and the market structure. Such a model is generally based upon a population of heterogeneous competing firms which interact in the same market and which perform their own innovative activities. This kind of model has been developed in the tradition of Nelson and Winter (1982) and Winter (1984)⁷ and aims at being consistent with a co-evolutionary view of technological change. These models are micro-founded models where every action is taken by the individual agents (producers or buyers) who are influenced by the aggregate state of the system - i.e. the industry -. The aggregate values derive simply from the calculus of individual states of the elementary entities that in turn, react to the stimuli coming from their external environment on the basis of their internal state. The result of the model is a sort of "virtual history" in which, at different levels of aggregation and time scales, different properties and phenomena appear, evolve and disappear. In this perspective, some authors propose to replicate the history of an industry evolution with formal models "that aim to capture the gist of the appreciative theory put forth by analysts of the history of an industry or a technology and thus to enable its logical exploration" (Malerba et al., 1999). So this type of approach gives us a relevant framework to explore the interdependencies between the trajectories of clean technology developed by firms and the evolution of market structure. Our purpose is not to replicate any history, but to propose a model which captures some of the stylised facts discussed in previous section concerning clean technology.

In order to represent the trajectory of clean technology, we have to include the various attributes, in the sense of Lancaster, that are affected by the implementation of clean technology. As argued in section I, we have to take into account simultaneously the productive efficiency of the production process, its environmental quality and the performances of the product. A trajectory of clean technology will be characterised by the evolution of these different attributes that are determined by the innovative activities of firms. Each trajectory of clean technology will be specific to one firm and determined by its R&D activities. On this point, our modelling of the innovation process takes into account the main stylised facts on technological change, that are specificity, uncertainty and cumulativeness (Dosi, 1988).

Firstly the property of *specificity* implies that each firm is endowed with an innovation process which rests on its own technological competencies. Firms carry out R&D activities according to particular rules of investment that lead them to accumulate technological

⁷ For a survey of this kind of model, see Silverberg and Verspagen (1995) and Windrum (1999).

knowledge and competencies that are firm-specific. In our model, these rules are fixed in order to characterise the bounded rationality of the firms which have to cope with the uncertainty inherent to innovative activities and with the environmental risk raising from the lack of knowledge about environmental impacts. Moreover we assume that firms invest in two distinctive types of R&D : the "environmental R&D" and the "productive R&D". The purpose of the environmental R&D is to increase the gross environmental performance of the production process, whereas the productive R&D aims at improving the productive efficiency of the production process and the performances of the product. This distinction is essential since the share dedicated to one type of R&D or another reflects the firm's bet as to the most useful direction to proceed under the constraint of environmental regulation. Firms are heterogeneous in their choices that are based on how they perceive their competitive situation and the way environmental criteria can affect their performances. By devoting a specific budget to environmental R&D, firms prove to be aware of the potential of opportunities opened by the environmental dimension that can be a source of innovation and technological progress. So we account for the diversity of firms' strategies as regards environmental opportunities by sharing R&D efforts according to both search directions (environmental and productive). This differentiated sharing of R&D expenditure enables us to grasp different patterns of innovation that will be at the origin of the different trajectories of clean technology.

The second property of *radical uncertainty* is inherently associated with innovative activities. On this point we assume that firms have to face a random process which distribution of probabilities is not known. So in our model we introduce innovation as a stochastic process depending on each type of R&D. Like in most evolutionary models of industrial dynamics, we follow a two steps procedure to formalise the process of innovation. The first step aims at determining the occurrence of the innovation by making a random draw according to a probability function which depends on R&D investment. The second step consists in determining the result of innovation -in case of success- in terms of performances. In our model the outcome of innovation result from a deterministic process of technological improvement that depends on several factors : the amount of R&D resources available for the type of innovation (environmental or productive), the cumulated experience in advancing on a particular trajectory and the predefined technological constraints that limit the technological feasible increments⁸.

Finally the property of *cumulativeness* of innovation implies that the choice of a technological option at a particular moment in time determines the future improvements of this solution. Cumulativeness is a source of path-dependency which causes irreversibility in the development of the production process and which can lead to lock-in phenomena, when one technological trajectory is selected at the expense of another more efficient one. This involves to include path-dependency in the set of equations guiding the evolution of technological trajectories of firms. It is the reason why, for each firm, the technological improvement resulting from innovation will depend on the level of the considered attribute at previous period. In this context for each firm, the innovative draws determine the evolution of the attributes that are affected by the implementation of clean technologies and that define the performances of the product for buyers. Our model is typically a supply model and we do not take into account explicitly the preferences and the micro-decisions of buyers. We only focus on the decisions of the industrial suppliers that are supposed to sell their products on the

⁸ This deterministic process depends on the models of industrial dynamics. In some models, the second step of the procedure, that is the result of innovation, is also assumed as random.

market without any demand constraint. For the dynamics of the market, we assume that the demand is positively correlated to each attribute and to the weight of each supplier on the market. Thus the industrial dynamics is driven by innovative activities of firms in clean technology and by the competitive interactions on the market.

The heterogeneity of firms and the random processes of innovation involve non-linear dynamics. More precisely the considered random processes are non stationary and non ergodic. As a consequence, the traditional analytical tools of stochastic dynamics can not be applied. The use of simulations provides a way of studying and observing step by step the evolution of this type of dynamic system. Since our purpose is to compare various trajectories of clean technology resulting from different innovative strategies of the firms competing on the same market, the use of simulations enables us to capture the logical exploration of different patterns of innovation in clean technology and their long-term evolution embedded in the industrial dynamics. A simulation model is an interesting way of identifying some emergent properties concerning the interactions between the innovative strategies in clean technology and the competitiveness of firms. In other words, it provides us a tool to explore the interdependencies between the trajectories of clean technology and the evolution of the market structure.

II.2 The dynamics of the model of clean technology

We now turn to define the specific dynamics of our model of clean technology. In the following boxes 1 and 2, we explicit in details the mechanisms underlying the process of environmental innovation and the market dynamics. We try to give the formal counterpart of the framework such as presented in the first section.

The model deals with a population of heterogeneous firms which produce an equipment good which is sold to industrial customers. It means that the suppliers and the industrial purchasers of the product are vertically related⁹. Since our model is a supply model, we focus on the decisions of industrial suppliers. The technological competencies of suppliers are characterised by three attributes: the productive efficiency of the production process (A_p), the gross environmental performance of the production process (I_p) and the performances of the equipment good (P_e). These three attributes define a set of indicators of the global performance, in productive and environmental terms, of industrial suppliers.

Firms start with the same initial technological competencies. Then firms assign different fractions of their periodical R&D budget to efforts in order to improve the productive efficiency and the environmental quality of their production process, as well as the performances of the product itself. Investments in environmental R&D are devoted to improve I_p , whereas investments in productive R&D aims at improving A_p and P_e . Thus after the initial period, firms will be differentiated in terms of their innovative strategy in clean technology and will achieve equipment goods endowed with different characteristics. Although the improvement of each attribute results from R&D investment of firms and from their experience, they also have to cope with technological constraints on each attribute. These constraints define the space in which firms try to progress gradually through their innovative strategy in clean technology. In conformity with the argument developed in section 1, we take into account two different paradigms defined in the two-dimensions space (A_p, I_p) - e.g. solvent and without solvent-. They are differentiated in terms of their potential of

⁹ The structure of the model is inspired by Chiaromonte and Dosi (1992).

improvement in environmental performances. At the beginning of the history, there is a single paradigm (solvent) which provides a relatively high potential of productive efficiency compared with its environmental performance. Later under the pressure of environmental regulation, a new paradigm (without solvent) comes into interest for firms. The second paradigm enables a potential of dramatic improvement along the environmental dimension that is permitted by the use of technologies without solvent. This major difference of environmental potential between the two paradigms leads us to take into account a 'competence destroying' effect of technological change when crossing the environmental outer limit of the first paradigm. This effect stands for the need for the firms that change paradigm to implement a radically new technology and to develop a new product, and so to overcome a new phase of learning and experience.

Box 1 The process of environmental innovation

In order to progress in the space of clean technology and to expand their market shares, firms have to invest resources in R&D. Two types of R&D investment are considered: the productive R&D ($RA_{i,t}$) and the environmental R&D ($RI_{i,t}$). The productive R&D is devoted to increase the productive efficiency and the performances of the product, whereas the environmental R&D is dedicated to the improvement in the environmental performance of the production process. The total amount of R&D resources is a proportion μ of the turnover $T_{i,t}$ specific to each firm i at period t : $RI_{i,t} = \mu T_{i,t}$ (1)

We assume that firms invest their whole turnover in R&D ($\mu = 1$). Then we determine the amount of R&D investment distributed between both types of R&D:

$$RA_{i,t} = \delta_i \cdot RI_{i,t} \quad (2)$$

$$RI_{i,t} = (1 - \delta_i) \cdot RI_{i,t} \quad (3)$$

The parameter δ_i (contained between 0 and 1) is firm-specific and determines the sharing of R&D resources between productive efficiency and environment. The role of this parameter is essential since it enables us to distinguish between different innovative strategies in clean technology performed by firms.

To both types of R&D correspond a type of innovation: productive and environmental innovation. In each case, the process of innovation follows a procedure in two steps in order to determine first the occurrence of innovation and its result in case of success.

The productive R&D determines the probability to innovate along the productive dimensions, i.e. Ap and Pe .

$$\Pi A_{i,t} = \frac{\pi_1}{\pi_2 + \pi_3 \cdot \exp(-\pi_4 \cdot RA_{i,t})} \quad (4)$$

This probability evolves according a logistic function bounded by the parameters π_1 , π_2 and π_3 . The parameter π_4 sets the speed at which the maximum probability is approached. This logistic function implies increasing and then decreasing returns of R&D in the innovation process.

Two independent draws are realised with this probability of innovation in order to define the improvement in the production process and in the product.

First we specify the improvement in the productive efficiency of the production process as following:

$$\Delta Ap_{i,t} = \eta_0 \cdot RA_{i,t}^{\eta_1} \cdot E_{i,t}^{\eta_2} \cdot (Ap^{\max} - Ap_{i,t-1})^{\eta_3} \quad (5)$$

with

$$Ap^{\max} = Ap^{\max 1} \quad \text{if} \quad Ap_{i,t-1} \leq Ap^{\max 1} \quad \text{and} \quad Ip_{i,t-1} \leq Ip^{\max 1},$$

$$Ap^{\max} = Ap^{\max 2} \quad \text{if} \quad Ap_{i,t-1} > Ap^{\max 1} \quad \text{or} \quad Ip_{i,t-1} > Ip^{\max 1}$$

and $\eta_1 + \eta_2 + \eta_3 = 1$

$Ap^{\max 1}$ represents, inside the first paradigm (solvent), the outer limit that can be achieved with a logic of energy and resources savings. $Ap^{\max 2}$ stands for the outer limit (the technological frontier) that can be achieved with a logic of search for higher gains in productivity and effective competitive advantage. These two limits were not included in our first representation of the space of clean technology (figure 1), but were suggested implicitly by the progressive increase in productivity (energy and resources savings first, higher yields then). The transition from one logic to another involves the start of a new phase of learning from experience. $Ip^{\max 1}$ sets the

environmental limit that determines the first paradigm. $E_{i,t}$ represents an experience variable that expresses the fact that the accumulated competencies of a firm give to it a comparative advantage for a given amount of R&D. However these competencies are brought into question when the firm crosses $Ap^{\max 1}$ or $Ip^{\max 1}$ which leads to a decrease in $E_{i,t}$ (competence destroying effect).

Second we specify the improvement in the performances of the product as following:

$$\Delta Pe_{i,t} = \lambda_0 \cdot (Pe^{\max} - Pe_{i,t-1}) \quad (6)$$

This equation determines the variation in the performances of the product, given that every firm starts with a level of performances of the product equal to $Pe^{\min}$. λ_0 is a parameter which determines the speed of increase in the quality level of the product. We assume that the path of improvement of Pe is delimited between $Pe^{\min}$ and $Pe^{\max}$. According to this equation, the trajectory of Pe is characterised by decreasing returns. When a change in the paradigm occurs, that is when there is a transition from the first paradigm (solvent) to the second one (without solvent), firms have to cope with a 'competence destroying effect' due to the radical technological change. This effect is associated not only with a decrease in the experience variable, but also with a decrease in the performance of the product. In this case, Pe falls down to its minimum value $Pe^{\min}$.

The environmental R&D determines the probability to innovate along the environmental dimension according a logistic probability function similar to the one firstly used:

$$\Pi_{i,t} = \frac{\pi_1}{\pi_2 + \pi_3 \cdot \exp(-\pi_4 \cdot RI_{i,t})} \quad (7)$$

In case of success of environmental innovation, a firm is able to improve the environmental performance of its production process as following:

$$\Delta Ip_{i,t} = \eta_0 \cdot RI_{i,t}^{\eta_1} \cdot E_{i,t}^{\eta_2} \cdot (Ip^{\max} - Ip_{i,t-1})^{\eta_3} \quad (8)$$

with $Ip^{\max} = Ip^{\max 1}$ if $Ip_{i,t-1} \leq Ip^{\max 1}$, $Ip^{\max} = Ip^{\max 2}$ if $Ip_{i,t-1} > Ip^{\max 1}$,

and $\eta_1 + \eta_2 + \eta_3 = 1$

$Ip^{\max 1}$ and $Ip^{\max 2}$ represent the outer limit that can be achieved along the environmental dimension of respectively the first paradigm and the second paradigm. Thus the parameters $Ap^{\max 1}$, $Ap^{\max 2}$, $Ip^{\max 1}$ and $Ip^{\max 2}$ specify the two dimensions technological space (in the same perspective as figure 1) in which we are going to simulate the trajectories of clean technology of firms.

We assume that, on the basis of the set of attributes, the industrial suppliers evaluate the global performance of their product through what we call a 'merit' function. Insofar as we are in a configuration where producers and users are vertically related, we consider that they specify jointly the characteristics of the product. We assume that industrial purchasers address requirements that do not concern directly the price of the product but its technological characteristics in terms of product quality (Pe), as well as the environment-friendly way with which the equipment goods are produced (Ip). These environmental considerations are mainly linked to regulatory pressure. From the perspective of industrial suppliers, the global performance of the product will rely on its capacity to fulfil the specifications of their industrial clients. But this global performance will also depend on the productive efficiency of the production process (Ap) since it determines the production costs and consequently influences the price of the product. So we argue that these three attributes do matter for the industrial purchasers of the product. This leads us to specify the following industrial dynamics.

Box 2 The market dynamics

The evaluation made by industrial suppliers of their global performance is defined by the following Cobb-Douglas 'merit' function¹⁰:

$$M_{i,t} = (Ap_{i,t})^{\beta_1} \cdot (Ip_{i,t})^{\beta_2} \cdot (Pe_{i,t})^{\beta_3} \quad (9)$$

with $\beta_1 + \beta_2 + \beta_3 = 1$

With this function, the merit of the product is an increasing function of each attribute and the relative increase in merit is a weighted average of the relative increases in each attribute.

We assume that this merit function has a positive impact upon the number of products to be sold by a firm. In order to grasp this relation between the merit and the quantity of products to be sold, we define a competitiveness factor which is a Cobb-Douglas function of the merit of the product and of the market share of the firm at the previous period¹¹. The market share of a firm is determined according the quantity of products sold:

$$S_{i,t} = \frac{N_{i,t}}{\sum_i^n N_{i,t}} \quad (10)$$

with $N_{i,t}$ the number of products sold by firm i at period t and n the number of firms in the industry.

Thus we assume that the higher the merit of the product and/or the market share of the firm, the more competitive it is. The competitiveness factor is given by the following equation:

$$Nc_{i,t} = \gamma_0 \cdot M_{i,t}^{\gamma_1} \cdot S_{i,t-1}^{\gamma_2} \quad (11)$$

with $\gamma_1 + \gamma_2 = 1$

Two important aspects go through the competitiveness factor: the positive relationship existing between the merit of the product and each attribute and the market interactions with the evolution of firms' market shares.

The number of products to be sold by each producer at period t ¹² depends on this competitiveness factor:

$$N_{i,t} = \varepsilon_i \cdot N_{i,t-1} + (1 - \varepsilon_i) \cdot Nc_{i,t} \quad (12)$$

This function characterises the dynamics of the market which exhibits path-dependency since the number of products sold at the current period depends on the previous quantity of products sold.

Concerning the price of the product, we assume that each firm sets its own price according to the productive efficiency achieved with the production process and to the performances of the product itself.

$$P_{i,t} = \alpha_i \cdot \sqrt{\frac{Pe_{i,t}}{Ap_{i,t}}} \quad (13)$$

With this price function, two opposite effects are considered: the price is decreasing with the productive efficiency of the production process (Ap) whereas it is increasing with the improved quality of the product. (Pe). The first effect reflects economies of resources or gains in productivity. The second effect is linked to a 'quality effect' that enables firms to set price premium when the product sold has a better performance.

Given the considered dynamics of the market, we finally determine the turnover of each firm :

$$T_{i,t} = P_{i,t} \cdot N_{i,t} \quad (14)$$

Within this model, firms are able to innovate on three dimensions and to combine different types of innovations which determine their trajectory of clean technology. Our purpose is to examine the impact of these various innovations on the evolution of the competitiveness of firms and so the industrial structure.

¹⁰ This function is inspired by Malerba et al. (1999).

¹¹ The competitiveness factor enables us to translate the merit of the product into the number of products sold.

¹² Since we assume that each supplier has the capacity to satisfy the demand, $N(i,t)$ is implicitly the effective supply of products of firm i at period t .

III. The efficiency of the three stylised trajectories of clean technologies : results of simulations

The model is implemented in a new programming system called LSD (Laboratory for Simulation Development) dedicated to the development of models of industrial dynamics¹³. This modelling platform provides a standardised and convivial tool to implement these types of model. In order to run our simulations, we use a specific settings of parameters (see Appendix A.1). This numerical specification does not intend to be consistent with empirical data. Our purpose is to show, through theoretical simulations, how the performances of firms competing on the same market, can be affected by the different combinations of productive and environmental improvements at the process and product levels.

We consider a population of twelve firms on the market and we specify three different sharing of R&D investments between productive R&D and environmental R&D. A group of four firms will devote 90% of their R&D budget to productivity R&D. In a second group of four firms, 90% of the R&D investment will be dedicated to the environmental quality of the production process. In the last group, four firms will combine equally the two directions of search and devote 50% of their R&D to environmental R&D as well as to productive R&D. This differentiated allocation of R&D resources enables us to illustrate again the three stylised trajectories of clean technology that result from specific innovative strategies -productive, environmental and median-. So we respectively call each group of firms, the PROD-firms, the ENVI-firms and the MEDI-firms.

The results of simulations derive from a *protocol of simulation* in three stages. First we run a battery of 50 simulations -each simulation being 100 periods long- in order to identify the general pattern of evolution of each group of firms according to their innovative strategy in clean technology. The distribution of the main variables of the model are presented in the appendix A.2. For each variable (A_p , I_p and P_e), the boxplots summarise the information relative to each group of firms at two different moments in time, $t=50$ and $t=100$. As expected, the results of the battery of simulations show that PROD-firms exhibit the highest performances on A_p and P_e in the two periods considered, while they perform badly on the environmental dimension. This result is achieved even if these firms never switch to the new paradigm. Their advantage comes from their ability to be fast in progressing on the dimensions in which they are specialised (A_p and P_e). On the contrary ENVI-firms, that reach the second paradigm before period 50, progress more slowly on their own specialised dimension (I_p). At the end of the period, they do not exhibit a significant advantage on this dimension in comparison with MEDI-firms. In this respect, MEDI-firms also reach the second paradigm and they are able to catch up with ENVI-firms on their specialised dimension I_p and also with PROD-firms on A_p and on P_e in a slightest way. This is due to the fact that they progress simultaneously on each dimension, which is consistent with our assumption of a mixed strategy characterised by an equal sharing out of R&D between productive and environmental dimensions. However MEDI-firms are characterised by a relatively high dispersion on each attribute at the end of the period. This result suggests that the performances associated to the median strategy are rather heterogeneous. In terms of market shares (see Appendix A.2), the MEDI strategy appears to be the most efficient one in the long term in spite of a competitive disadvantage in the short term as regard to the PROD strategy.

¹³ This system has been developed by Marco Valente for IIASA (Austria) with researchers like Dosi, Nelson, Silverberg and Winter and for DRUID (University of Aalborg, Denmark) with Andersen. For more information, you can visit the LSD web site <<http://www.business.auc.dk/lsd/>>.

Finally this first stage enables us to grasp some regularities in the differentiated trajectories of firms.

III.1 The competitiveness of firms and their evolution in the space of clean technologies

In order to analyse the evolution of firms in the space of clean technologies, we represent the trajectory of firms in the two-dimensions space (A_p , I_p) and the evolution of the performances of the equipment good (P_e), respectively in figure 2 and figure 3.

Figure 2 : The evolution of firms in the space of clean technology

Figure 3 : The evolution of the performance of the product

Figure 2 shows that PROD-firms increase significantly the productive efficiency of the production process but that they remain with an environmental index inferior to the outer limit set by the first paradigm. So they never switch to the new paradigm. Concerning ENVI-firms, they change the paradigm since they cross the maximal frontier of the first paradigm. However they do not benefit from this switch in terms of productive efficiency and we observe that they stay below the maximal limit which is achievable with a logic of energy and resource savings. On the contrary, MEDI-firms succeed in combining the two dimensions and three firms over four reach the two maximal frontiers of the space of clean technologies. These firms perform a change of paradigm and exploit efficiently the technological potential.

As to the evolution of the performance of the product, figure 3 shows the competence destroying effect due to the change of paradigm experienced by ENVI-firms and MEDI-firms. In spite of the change of paradigm, the MEDI-firms reach a relatively high level of performance of product. This effect results from their specific innovative strategy which relies upon a significant proportion of R&D investment devoted to productive R&D that enables them to support product innovations. On the contrary ENVI-firms do not benefit from this outcome and so they pay for the competence destroying effect. This demonstrates the advantage of leading two types of R&D in order to be able to compensate and to enhance the competence destroying effect associated with the change of paradigm. For example, the firm that invests in environmental R&D to find a glue without solvent has an interest to change complementarily the product in which the glue is used. Finally the moment of change of paradigm seems to have an impact on the performance of the product performed by MEDI-firms, since we observe that the later the MEDI-firms change of paradigm, the more difficult they start again and evolve on the trajectory associated to the performance of the product (P_e).

In order to illustrate the performances associated to each strategy, we present the evolution of firms' market shares over the simulation period (figure 4). We propose to stress three main phases in the evolution of market shares. In the first phase, which spreads from period 0 to period 30, PROD-firms and MEDI-firms tend to increase their market shares whereas ENVI-firms are characterised by a decrease in their market shares. This is due to the fact that ENVI-firms do exclusively progress on one dimension (I_p). Moreover, during this period, ENVI-firms change of paradigm and consequently suffer from the destroying competence effect. The second stage, which extends until period 50, is determined by the change of paradigm by MEDI-firms. This stage of transition is of major importance since the competence destroying effect undergone by MEDI-firms leads to a significant drop in their market shares. Consecutively, this leads to a restructuring in the market shares of the different groups of firms. The third stage is characterised by the progressive consolidation of the competitive advantages of MEDI-firms. At the same time, this stage corresponds to the saturation of technological opportunities for PROD-firms that stick in the first paradigm. These two effects are self-reinforcing and they transit through the market interactions in such a way that they emphasise both the decrease in the market shares of PROD-firms and the increase in the market shares of MEDI-firms. By difference, the ENVI-firms exhibit a stabilisation of their market shares during this period. At the final period, MEDI-firms hold the highest market shares with a total of 49.2%, against 32.4% for the PROD-firms and 18.4% for the ENVI-firms.

Figure 4 : The evolution of firms' market shares

These results lead us to raise three main conclusions. First the environmental strategy is not efficient in the long run because the change of paradigm is exclusively drawn towards the environmental quality of the production process (I_p) and is not associated with gains in productivity. This case is illustrated by the technology of thermal scrubbing with fluidised bed combustors which only allows for energy and resource savings (cf. figure 1 page 6). Although this technology succeeds in eliminating chlorinated solvents, it does not come through the achievement of gains in productivity. This example suggests that a radical innovation that permits a significant decrease in the gross emissions of the production process (increase in I_p) is not sufficient and that it should be combined with other innovations. Second the productive strategy turns out to be efficient in the short term. This is reflected by a phase of dominance of PROD-firms in terms of market shares during the first phase. Nevertheless the situation gets reversed in the long run when the PROD-firms find to be locked in the first paradigm where they have to cope with the running out of technological opportunities. Even the continuous increase (at a decreasing rate) in the performance of the product does not compensate this lock-in effect in the first paradigm. This illustrates that the gains in productivity achieved with the productive strategy -beyond the logic of resource and energy savings- are only a source of competitive advantages in the short term. Finally, the median strategy appears to be the most efficient one in the long run. This strategy enables to exploit efficiently the space of clean technology since they succeed in getting a simultaneous and sustained improvement in the three dimensions. We can also observe, on the one hand, that the change of paradigm is associated with gains in productivity and on the other hand, that these gains in productivity are a source of competitive advantages in the long run. So the median strategy requires to take a risk in the short term in order to bear the disadvantages arising in the first moment of competition with the PROD-firms.

III.2 Policy implications

Our main argument is that, from the policy point of view, the most efficient trajectory of clean technology is the one followed by MEDI-firms. This trajectory enables an efficient change of paradigm which opens significant technological opportunities on the environmental dimension and on the productive ones. In the case of the regulation of emissions of VOCs,

this would correspond to the change from the solvent paradigm to the new paradigm without any solvent (cf. §I.2). This type of trajectory of clean technology does not only lead to a change of paradigm, but also to the growth of firms. Indeed MEDI-firms end up with higher market shares than ENVI-firms for which the change of paradigm is associated with very low market shares. It is the reason why we argue that the trajectory of MEDI-firms is the best to comply with an objective of sustainable development. So we consider that the fundamental purpose of public policy is to promote trajectory of clean technology of the median type, which can be called 'sustainable clean technology'.

The simulations stress two main difficulties for MEDI-firms :

The time for return on investment seems to be very long since the gain in market shares occurs in the long run (cf. Figure 4). An efficient change of paradigm needs to progress simultaneously on the environmental and the productive dimensions which takes more time than to progress on one single dimension.

The change of paradigm brings a destroying competence effect which tends to decrease the market shares of MEDI-firms.

These results suggest that there is a need for public support for the firms developing this kind of clean technology. This is the main purpose of the R&D support given by the French environmental agency (ADEME) to firms involved in research projects on clean technology. But this point emphasises an important issue since generally environmental subsidies must only cover environmental costs. As a matter of fact, the subsidy given by ADEME is proportionally decreasing with the gains in productivity linked to the adoption of clean technology, since ADEME does not want to support the production apparatus and to create impediments to competition. But our case studies and simulations show that the efficiency of an innovative strategy in clean technology depends on the ability of firms to combine productive and environmental performances. This points out that trajectory of clean technology could be stimulated by coupling environmental support with innovation subsidies.

As to the destroying competence effect, it is a typical problem when dealing with the adoption of radical innovations. In the field of technology policy, several examples show that R&D cooperation enables firms to overcome more rapidly this effect (see for example Hagedoorn et al., 2000). So it could be of interest to develop cooperative R&D agreements for clean technology. In this respect, we have already observed a case of pre-competitive R&D consortium in the chemical sector for the development of ionic liquids¹⁴.

In order to complete our analysis of policy implications, we also consider the role of the parameters governing the weight of productive and environmental constraints. In our model, the weight of environmental and productive constraints correspond to the parameters β_1 , β_2 and β_3 in the function of merit (equation 9)¹⁵. They determine the relative effect of the variation of each attribute upon the variation of the merit of the product. We can argue that β_1 represents the competitive pressure among suppliers in terms of efficiency of the production

¹⁴ Ionic liquids are heavy liquids which do not evaporate and do not reject any VOCs. They represent a promising alternative to chlorinated solvents. It exists a pre-competitive research consortium dedicated to this topic, called QUILL (Queen's University Ionic Liquid Laboratories), which links industrial firms and public research laboratories.

¹⁵ In the reference case presented in section II, we consider a rather equal distribution of the weight between the different constraints by assuming $\beta_1=0.3$, $\beta_2=0.3$ and $\beta_3=0.4$.

process. As to β_2 , it represents the impact of environmental performances on the merit of the product and consequently, on the number of products to be sold. This effect is linked to the environmental pressure which can result from environmental regulation and/or from the environmental requirements of industrial purchasers (subjected themselves to environmental regulation). The last parameter β_3 stands for the weight of the requirements of industrial purchasers in terms of performances of the product. Our purpose is to study how the interactions between these different constraints influence the dynamics of evolution in clean technology of the three main groups of firms (PROD, MEDI and ENVI). Appendix A.3 presents some results of simulation with different values of β s.

These results show that an increase in β_3 tends to stimulate the relative growth of MEDI-firms which become earlier dominant in terms of market shares (cf. figures in Appendix A3). This is due to the fact that the requirements of industrial purchasers give incentive to increase the performances of the product, which contributes to the development of MEDI-firms in the long run. It shows that strong vertical interactions can favour the development of sustainable clean technology. A second result is that an increase in the regulatory pressure (increase in β_2) is conducive to a rise in the performances of ENVI-firms and MEDI-firms. This result underscores that the regulatory pressure is one of the favourable conditions to the development of sustainable clean technology.

The two examples of sustainable clean technology given in section I.2 are linked to these arguments. Indeed the technology of treatment of surfaces with low temperature plasma has been developed by the metallurgical industry which is strongly concerned with the vertical pressure coming from the industrial clients of the automotive and aircraft industries. This promising clean technology is now supported by an European programme of cooperative research. As to the case of heliography with water-based inks it is a typical example of a clean technology developed under the pressure of a stringent regulation. This technology concerns the printing industry which is subject to specific and strong requirements for the regulation of their emissions of VOCs. In this sector, the regulatory pressure clearly gives an incentive to innovation in sustainable clean technology. Finally vertical interactions and regulatory pressure appear to be the main policy dimensions in order to promote sustainable clean technology.

Conclusion

This paper develops a framework dedicated to the analysis of clean technology which is inspired by empirical patterns of environmental innovations linked to the regulation of VOCs emissions. Our case studies enable us to differentiate between three types of trajectories of clean technology represented in a two dimensions space. Each trajectory is characterised by a specific combination of improvements in environmental and productive performances. We present a micro-simulation model which enables us to depict these different trajectories of clean technology and their influence upon the evolution of industrial structure. The main result of the simulations is that the firms following what we call the median strategy end up with the highest total market share in the long run. This median strategy is characterised by a good balancing between environmental and productive R&D which allows firms to progress simultaneously on each dimension and to switch to a new paradigm. The trajectory resulting from this strategy can be defined as a sustainable trajectory since it combines environmental progress, gains in productivity and growth of firms.

In terms of policy implications, our analysis calls for a coordination of environmental and technology policies in order to help firms to perform product and process innovation offsets. Moreover a brief study of the role of the parameters governing the weight of productive and environmental constraints suggests that vertical relationships between industrial suppliers and clients, as well as regulatory pressure, can stimulate the development of sustainable clean technology. However all these arguments should be considered cautiously since the trajectory of clean technology is conditioned by the characteristics of industrial sectors.

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APPENDIX A.1 : VARIABLES and PARAMETERS

• INDUSTRY LEVEL

	NAME	MEANING	INITIAL VALUE	COMMENT
<u>Parameters</u>	β_1	Elasticity of the merit of the product according to A_p	0.3	$\beta_1 + \beta_2 + \beta_3 = 1$
	β_2	Elasticity of the merit according to I_p	0.3	
	β_3	Elasticity of the merit according to P_e	0.4	
	γ_0	Scale parameter	10	
	γ_1	Elasticity of competitiveness according to the merit of the product	0.5	$\gamma_1 + \gamma_2 = 1$
	γ_2	Elasticity of competitiveness according to the market shares (Bandwagon effect)	0.5	
	$P_e^{\max}$	Maximum performance of the product	50	
	$P_e^{\min}$	Minimum performance of the product	4	
	$A_p^{\max 1}$	Outer limit of productive efficiency achievable with a logic of resource and energy savings in the first paradigm	4	
	$A_p^{\max 2}$	Outer limit of productive efficiency achievable with a logic of search for gains in productivity	14	
	$I_p^{\max 1}$	Outer limit of environmental performance determined by the first paradigm	3	
	$I_p^{\max 2}$	Outer limit of environmental performance determined by the second paradigm	13	

• FIRMS LEVEL

	NAME	MEANING	INITIAL VALUE			COMMENT
<u>Parameters</u>	α	Mark-up rate	1			
	μ	Proportion of turnover invested in total R&D	1			$\mu = 1$
	δ	Proportion of total R&D dedicated to productive R&D	PROD 0.9	MEDI 0.5	ENVI 0.1	1- δ stands for the percentage of total R&D dedicated to environmental R&D
	π_1	Parameter for the probability to innovate	0.035			
	π_2	Parameter for the probability to innovate	0.05			
	π_3	Parameter for the probability to innovate	0.65			
	π_4	Parameter for the probability to innovate	0.4			
	η_1	Impact of R&D upon productive and environmental innovation	0.45			
	η_2	Impact of experience upon productive and environmental innovation	0.1			
	η_3	Impact of the distance to the frontier $A_p^{\max}$ or $I_p^{\max}$ upon productive and environmental innovation	0.45			
	λ_0	Speed of exploitation of the trajectory P_e	0.05			
	η_0	Improvement step resulting from the success of productive and environmental innovation	0.05			
	ε	Weight of past sales in the current sales of the product	0.5			1- ε stands for the weight of the competitiveness factor in the current sales
<u>Initialisation of</u>	P_e	Performance of the product	4			

<u>Variables</u>	Ap	Productive efficiency of the production process	1 1	
	Ip	Environmental quality of the production process	1 1	
	M	Merit of the product	1	
	S	Market shares	1/12	
	N	Number of products sold	10	
	E	Experience variable	1	

APPENDIX A.2 : Results of a battery of 50 simulations

Boxplot for A_p at time $t=50$

Boxplot for A_p at time $t=100$

Boxplot for I_p at time $t=50$

Boxplot for I_p at time $t=100$

Boxplot for P_e at time $t=50$

Boxplot for P_e at time $t=100$

Boxplot for S at time $t=50$

Boxplot for S at time $t=100$

APPENDIX A.3 : Results of simulation for different values of β_s

Figure 5 : $\beta_1=0.6$ $\beta_2=0.3$ $\beta_3=0.1$

Figure 6 : $\beta_1=0.35$ $\beta_2=0.3$ $\beta_3=0.35$

Figure 7 : $\beta_1=0.1$ $\beta_2=0.3$ $\beta_3=0.6$

Figure 8 : $\beta_1=0.25$ $\beta_2=0.5$ $\beta_3=0.25$

Figure 9 : $\beta_1=0.2$ $\beta_2=0.6$ $\beta_3=0.2$

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