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Dura lex sed lex: why implementation gaps in environmental policy matter?

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Dura lex sed lex : pourquoi le décalage entre les intentions et les actes en matière de politique environnementale importe-t-il ?

Résumé

Nous étudions les décalages entre les intentions et les actes observés en matière de politique environnementale dans le cas spécifique de substances dangereuses visées par le règlement REACH. Un modèle à base d'agents est développé en tant qu'outil exploratoire. Il vise à examiner dans quelle mesure des écarts importants entre des exigences strictes et une mise en œuvre réelle mais conditionnelle de la politique affectent la manière dont des acteurs hétérogènes perçoivent la menace réglementaire et définissent leur stratégie d'innovation, compromettant potentiellement la transition vers des substituts plus sûrs. Nous montrons que l'application à la lettre d'une réglementation très ambitieuse sur des délais très courts ne conduit pas nécessairement à la plus forte probabilité d'interdiction des substances dangereuses, car une telle pression réglementaire est susceptible de modifier le jeu concurrentiel indispensable pour préserver la diversité des stratégies d'innovation des firmes et développer des substituts plus sûrs. Opter pour une réglementation très ambitieuse devrait alors aller de pair avec des concessions quant à la mise en œuvre de celle-ci afin de préserver un degré suffisant de diversité sur le marché et d'offrir aux firmes pionnières en environnement le temps nécessaire pour se développer. A l'inverse, si les autorités souhaitent appliquer la politique à la lettre, il peut être opportun de modérer le degré d'exigence de celle-ci afin de renforcer les perspectives de transition technologique.

Mots-clés: transition technologique ; pression réglementaire ; perception ; mise en œuvre de la réglementation ; règlement REACH ; modélisation à base d'agents

Dura lex sed lex: why implementation gaps in environmental policy matter?

Abstract

We investigate implementation gaps observed in environmental regulations in the specific case of dangerous chemical substances such as targeted by the REACH regulation. An agent-based model is developed as an exploratory tool to examine to what extent significant implementation gaps between stringency requirements and real but conditional enforcement jeopardize the transition to safer substitutes, by affecting the way heterogeneous actors perceive the regulatory threat and their innovation strategy. We show that the combination of the most severe regulation with the strictest enforcement and the shortest timing would not necessarily lead to the highest frequency of bans on dangerous substances, because it may alter the competitive process that is vital to preserving diversity in innovation strategies and to developing safer substitutes. Opting for a very severe regulation should be combined with concessions on enforcement in order to preserve diversity and to give green pioneering competitors enough time to expand. From a reverse angle, if authorities are keen to apply the regulation strictly and are prepared to face higher market concentration, then they should release the degree of stringency in order to enhance the prospects of transition to safer substitutes.

Keywords: technological transition; policy stringency; perception; enforcement; REACH regulation; agent-based model

JEL: O33, Q55, D83, Q58, C63

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1. Introduction

A number of objectives that are difficult to reconcile often affect environmental policies and their enforcement. As illustrated by numerous examples in the European Union, Directives that start out with the best of environmental intentions can end up with very poor efficacy (Castell et al., 2004). Negotiation rounds and lobbying take place and many considerations other than the protection of the environment such as competition distortions, job protection, relocation risks or adverse trade effects come to the debate, leaving room for policy trade-offs[1] and ultimately resulting in less ambitious environmental targets and a delayed or postponed schedule. The question is then how to deal with the fact that, on the one hand the sooner and stronger the policy response is, the shorter the slow growth transition phase (Acemoglu et al., 2012), but on the other hand, very stringent policies cause side-effects on key aspects of firms' competitiveness, including trade, industry location, employment, productivity, and innovation (Dechezleprêtre and Sato, 2017). These various economic and social impacts of environmental regulations stir up more or less legitimate opposition to the regulation and partly explain negotiations and lobbying. Typically, the withdrawal of substances from the market and product bans force industrial concentration and cause disruption in supply chains, thus bringing consequences for the market structure as well as entry barriers. In this regard, the current environmental policy framework fails to capture the potential harm caused to the market and more generally the dynamic implications of performance standards sanctioned by a product ban. In this article, we examine the combined effects of different stringency levels of environmental policy (in terms of performance targets and timing) with different enforcement thresholds on the success of a new, cleaner technology. We do so by focusing on the specific case of the substitution of dangerous chemical substances such as targeted by the REACH regulation (Regulation EC No 1907/2006 concerning the Registration, Evaluation, Authorization and Restriction of Chemicals), and by using an agent-based model to explore the dynamic interplay between environmental regulation and innovation.

The underlying question is to what extent policy stringency may stimulate innovation. Since the seminal article of Porter and van der Linde (1995) highlighting the central role of innovation as a way to (over)comply with environmental regulation, it is quite clear that environmental policy may stimulate eco-innovation but only on the condition that it is properly designed (Porter and van der Linde, 1995; Jaffe et al., 2005). In addition, an appropriate mix of innovation and environmental policies is seen as a crucial factor in directing economic systems towards sustainable and competitive paths of economic growth (van den Bergh et al., 2007).[2] Previous empirical studies also show that the degree to which the requirements of a regulation are strictly enforced may influence the willingness of an industrial sector to attempt to innovate (Ashford et al., 1985). Though insufficient stringency is likely to bring too little innovation, care must also be taken not to design and enforce standards so stringently that the regulated industry perceives massive noncompliance as the logical result. In this latter case, the perception of massive noncompliance may serve as a disincentive to innovate since

[1] Using metaphorical language regarding the European Union's waste electrical and electronic equipment Directive, Castell et al. (2004) refer to the proverb "*a camel is a horse designed by a committee*" to illustrate the gap between the initial idea and the final result. "*In the steps from the idea to the reality of legislation, the intent can be lost, and the horse can become a camel*" (p.4).

[2] As pointed out by Costantini and Mazzanti (2012), "there is increasing consensus on the potential win–win effects deriving from well combined environmental and innovation strategies, both on the private and public side" (Jaffe et al., 2005).

widespread noncompliance could result in an amendment of the compliance deadlines. Without going so far as to discredit the regulation, such implementation gaps between the requirements displayed by the regulation and its enforcement (for example because of significant likely failures and market exit) may still have consequences on the way firms in the regulated industry perceive the stringency of the policy and ultimately innovate.

This article analyzes whether significant implementation gaps between stringency requirements and real but conditional enforcement jeopardize the transition to cleaner technologies and/or safer substitutes, by affecting the way heterogeneous actors perceive the regulatory threat and their innovation strategy. We address three issues: policy design in terms of stringency and timing, credibility of the regulatory threat, and diversity of innovation strategies. Brouillat et al. (2018) have addressed all three questions together but only under the assumptions that the firm's decision to innovate remained unaffected by the postponement of the product ban and that enforcement was mechanically applied as soon as environmental objectives were achieved.[3] In this article, we extend the analysis to feedback that influences the credibility of the regulatory threat and to competitiveness considerations as an argument against the cutoff date to which the product ban is applied, leading to a risk of squeezing out too many noncompliant firms. The idea is that the risk of losses in competitiveness leads to a policy compromise such that the strict regulation is not enforced but rather postponed. However, repeated postponements of the product ban weaken the credibility of the regulation so that a growing gap between perception and intention of the regulation lowers the incentive to innovate. In turn, the need to preserve a larger number of firms in industries where the best innovation strategy is unpredictable is met, thus avoiding the risk of artificial concentration/monopolization and guaranteeing the competitive process through the persistent diversity of environmental strategies.

The article is organized as follows. Section 2 sets the conceptual background. Section 3 describes the model. Results are presented in section 4. Section 5 discusses those results. Section 6 concludes.

2. Literature background

2.1 Expected impact of environmental policy on competitiveness and innovation

From its beginnings in the early 1970s, the modern environmental policy has been used with increasing intensity and sophistication as the main instrument for coercing firms into internalizing the environmental costs of production (Parto and Herbert-Copley, 2007). These attempts to steer the behavior of economic agents in industrial production have not gone without opposition, on practical and ideological grounds. Environmental policy is conventionally assumed to impose significant costs and slow productivity growth, and thereby hinder the ability of firms to compete in international markets (Jaffe et al. 1995). In a revisionist view, driven by the Porter hypothesis (Porter and van der Linde, 1995) and today widely disseminated among policymakers, carefully designed environmental regulation is seen as a net positive force driving firms to enhance their competitiveness by encouraging innovation in environmental technologies. However, in addition to controversies about the empirical validation of the Porter hypothesis (Marin and Lotti, 2017), such an optimistic vision of

[3] Brouillat et al. (2018) show that objectively, high stringency results in a stable oligopoly after an early but short turbulent phase because of the ban on the dangerous substance. This phase is characterized by a significant reduction in demand, number of competitors, and number of available technologies. Subsequently, entry barriers are stronger and less entry is possible.

regulation does not yet seem to be widely accepted by industrial actors, and environmental policy is still viewed, at least in the short run, as an additional constraint generating costs to be incurred over and above the ‘‘normal’’ production costs (Parto and Herbert-Copley, 2007). The REACH regulation gives a perfect illustration and provides a useful empirical reference for our discussion.

REACH intends to promote substitution and radical innovation through an authorization procedure which is applied to firms who wish to continue to put particularly harmful chemicals on the market. Without authorization, the blacklisted substance cannot be placed on the market or used after a given date (sunset date). Authorization is granted only if no other economically and technically viable alternatives are available. Otherwise firms lose the right to produce and market them. Since its entry into force in 2007, two assessment reports have been carried out showing ambiguous effects for industry and diverging views as well as implementation gaps. In particular, the stakeholder consultation conducted for the second assessment report (European Commission, 2018a) shows that, “*according to industry respondents, REACH had negative effects on the competitiveness and innovation of the EU industry*” (European Commission, 2018b, p.12). Businesses and industry associations are the most critical stakeholder groups on this point. They consider that the regulation has *slightly* achieved the objectives of competitiveness and innovation. Such a negative view of environmental regulation would encourage firms to demand less ambitious environmental targets and delayed or postponed schedule when policy is designed or revised.

2.2 Damaging economic side effects of environmental policy

It is widely established that environmental policy is connected with economic issues such as trade (Barrett, 1994; Ulph 1996; Burguet and Sempere 2003; Fredriksson and Millimet 2002; Damania et al 2003; Greaker, 2003a; Ederington and Minier, 2003), relocation (Greaker, 2003b; Wagner and Timmins, 2009; Martin et al, 2014a, 2014b) or unemployment (Livermore et al, 2012; Babiker and Eckaus 2007; Walker, 2013; Martin et al, 2014a; Bartik, 2015; Gagliardi et al., 2016). The second REACH assessment report (European Commission, 2018a) exhibits several damaging economic side effects of the regulation, pointed out by industry stakeholders. Through the authorization process, the ultimate goal of the regulation is the progressive replacement of dangerous substances (so-called substances of very high concern) by suitable alternative substances or technologies. Strict enforcement of the authorization can then pose the risk for firms producing those dangerous substances of being pushed out of the market. According to industry stakeholders, “*compliance costs and risk management measures (e.g. authorization and restriction) have led to some extent to the relocation of activities outside the EU and the withdrawal of substances from the market, especially those produced in low volumes, forcing market concentration and causing disruption in the supply chains of certain products*” (European Commission, 2018b, p.12). As highlighted by Martin et al (2014b, p.2483), “*the threat of relocation - if credible - is a powerful argument to extract concessions from politicians of all stripes, as regulation-induced job losses are likely to cloud their reelection prospects*”. In this perceptive, several studies investigate political trade-offs between economic conditions and the environment (Kahn & Matsusaka, 1997; Kahn & Kotchen, 2011; Tanger et al., 2011; Jacobsen, 2013). They show that economic conditions can influence environmental policy with the general proposition of a positive relation between economic conditions (unemployment rate, per capita income) and pro-environment legislation. As a result, the extent of the environmental policy and its enforcement are not just about ecological and health concerns such that the purpose of the project is broadened, further watering down the original intent (Lévêque, 1996).

2.3 Environmental policy implementation gaps

The "capture" or "interest group" theory emphasizes the role of interest groups in the formation of public policy and explains the existence of gaps between initial intentions and effective implementation of environmental policies (Stigler, 1971; Peltzman, 1976; Dal Bo, 2006). Olson's (1965) theory of collective action is generally seen as a building block to explain how "*regulation is acquired by the industry and is designed and operated primarily for its benefit*" (p. 3). Laffont and Tirole (1991) show that in the presence of asymmetric firms, regulated firms are able to extract rents and therefore have an incentive to influence regulatory outcomes. However, industrial firms are not the only stakeholders in policy negotiation and their point of view is not necessarily shared by all. For instance, NGOs and consumer associations were much more positive than businesses and industry associations regarding the performance of REACH in terms of competitiveness and innovation.[4] In this perceptive, powerful consumer groups and NGOs can also have a role to play to ensure that government officials arbitrate among competing interests and not always in favor of business.

The absence of a credible monitoring and sanctions system is a second reason for implementation gaps (Cohen, 1999; Gray & Shimshack, 2011). In an extensive survey on monitoring and enforcement, Shimshack (2014) shows that inspections and sanctions directly reduce pollution, deter future violations, and even encourage beyond-compliance behavior. However, current environmental monitoring and enforcement practices do not appear to strictly maximize social welfare and often diverge from optimal enforcement. Monitoring and sanctions are sensitive REACH issues raised by stakeholders (European Commission, 2018a). They point out bad practices that compromise the enforcement of the "no data, no market" principle such as a high level of non-compliance of registration dossiers, free-riding in the preparation of joint submission and in the updating of registration dossiers, or the absence of sanction for non-compliant dossiers.

A third reason for implementation gaps is the existence of controversies and scientific uncertainty. Along with lobbying actions, such controversies are generally brought to the forefront of negotiations and can be crucial in raising doubts and questioning science, with the effect of blocking efforts towards implementing more sustainable forms of development (Jozel & Lascoumes, 2011; Henry, 2013; Godard, 1993; Stirling and Gee, 2002). As pointed out by Henry (2013, p.589), "*many powerful and well organized actors in the economy, in politics and in the media, are busy denying scientific results and fabricating more uncertainty than actually exists, in order to undermine policies that hurt their particular interests and ideological prejudices*". Controversies surrounding endocrine disrupting chemicals are an accurate illustration of the difficulty in regulating these new generation risks, or systemic risks with epistemic uncertainties (Renn, 2008).[5] Even in the absence of exact evidence of impacts, some analysts believe that the situation justifies reasonable concern over public safety and warrants precautionary policy action (Vogel, 2004; Hukkinen, 2008).

[4] NGOs consider that the regulation has *substantially* achieved the objectives of competitiveness and innovation (European Commission, 2018b).

[5] The risks related to endocrine disrupting chemicals are systemic, as the specific risks to human health and the environment have complex consequences for the larger socio-cultural context. The epistemic uncertainties derive from the lack of knowledge about fundamental phenomena underlying the chemical impacts. For new generation risks, quantitative risk assessment is particularly laborious, because specific outcomes and their probabilities are largely unknown, leaving few legitimate grounds for regulation. Nevertheless, new generation risks are at the same time often characterized by a considerable amount of experiential evidence collected and articulated by experts, commonly expressed as alternative scenarios describing the pathways and management of the uncertainties.

Ultimately, defining and implementing environmental policies requires the establishment of political compromises between environmental and/or health objectives and many other economic, social and political dimensions. Brouillat et al. (2018) make the simplifying assumption that the regulation is applied to the letter, with no flexibility as to its enforcement. In the present study we consider that the enforcement decision is taken by balancing environmental concerns and economic, social and political interests. More precisely, the enforcement of the regulation is conditional upon its impact on market outflow: enforcement will be applied only if "a minimum number of firms" is preserved. This minimum number is a threshold depicting the lower limit of the current number of competitors that is economically, politically and socially accepted by stakeholders. It is considered as the ultimate result of negotiation and lobbying that occur when policy enforcement is discussed. Giving a formal description of the processes at stake in such political negotiation is a very complex and tricky task that is out of the scope of this modeling exercise. This threshold will then be considered as an exogenous variable. It refers to the current number of competitors because the most direct and radical consequence of a strict enforcement of the authorization process is to reduce the number of competitors by pushing non-compliant firms out of the market in the first place. It is also a relevant criterion to address the different adverse side effects of the regulation, since unemployment, relocation risks, competition distortions or undesirable trade effects are (at least indirectly) linked to the number of competitors. In fact, a drop in the number of competitors due to a strict enforcement of the authorization may cause unemployment and/or relocation for the firms that were pushed out of the market.[6] Preserving a minimum number of firms is also a way to limit market power in order to control the risk of collusion and adverse trade effects.[7] Finally, in the context of multiple complex negotiations involving bounded rational agents, "preserving a minimum number of competitors" is a workable simple rule from which stakeholders are able to define a compromise as to the level of this threshold.

2.4 Perceived credibility of regulation

Whether the environmental policy has to deal with many competing interests (from different stakeholders) trying to capture regulation or with a phase of "collective learning" (Hatchuel, 2008) and changes in cognitive frames (Grin and van de Graaf, 1996), it leads to implementation gaps that, in turn, influence the way firms in the regulated industry perceive the policy stringency, *i.e.* their perceived credibility. As pointed out by Johnstone et al. (2007), there is very wide variation in the perceived stringency of the environmental policy regime and, in many of the analyses undertaken, perceived policy stringency turns out to be the most important determinant of private environmental

[6] It is obvious that the impact of the regulation on unemployment and relocation is not systematic. One can even argue that the prohibition of the harmful substance may reduce unemployment by leaving the field open to safer alternative(s) and thus creating jobs for its production. However, such a positive effect on employment is only likely to occur later and would take time to materialize, while the job destruction linked to the ban on the harmful substance is immediate. It is also obvious that there are devices other than preserving a minimum number of firms to avoid or limit these undesirable side effects. However, formalizing such alternative measures is out of the scope of the present modelling exercise and it would dramatically complicate the model and blur its results.

[7] Admittedly, "a minimum number of firms to preserve" is an imperfect filter, especially since what constitutes the gauge of relevant competition on a market may not depend on atomicity. Market power and high concentration may both reflect and generate efficiency. However, in the case of a product ban, noncompliant firms can no longer market the product, thus leading regulation to artificially force market concentration. The risk of collusion between firms may consequently be higher. In order to preserve a competitive process which is vital to promoting competition while mitigating the threat of monopolization, authorities will set a condition on the minimum number of competitors to keep before strictly applying the product ban. Thus this filter helps screen against excessively harsh consequences of the concentration that ensues from the ban.

performance and innovation. Based on a wide-ranging empirical study undertaken in seven OECD countries, the authors emphasize that perception of the importance of a policy instrument may be influenced by the visibility and unpopularity of the instrument and the period in which it was introduced. They add that respondents may be strategically biased, over-reporting the influence of measures which they feel are not in their private commercial interest relative to other instruments.

The agency may itself show proclivity for enforcement and narrowly interpret the legal provisions. The analysis of the effects of environmental policies is often based on a representation of public authorities as benevolent, omniscient and credible: they pursue a public interest goal and not specific objectives such as gaining bureaucratic power; they are informed about the regulated industry, technology, abatement costs, etc.; the commitments they make related to their future actions (e.g., applying sanctions for noncompliance) are credible in the eyes of those who would be affected by them. When an imperfect world is considered from the point of view, for instance, of information sharing, administrative costs or the public agency’s behavior, all instruments are imperfect (Börkey et al., 1998).

At this stage of the analysis, our intent is to take into account the fact that credibility assigned to the regulation by individual firms is endogenous, and is determined in each time period by reference to a regulatory framework. Credibility is formalized by a variable as a function of a set of environmental policy tools and firm-specific perception. Typically, recurrent postponements of the product ban decided upon in order to avoid competition distortions (e.g. higher industry concentration, relocation, shutdowns and job losses) at the expense of environment and health objectives lead to lower credibility and ultimately impact innovation.

2.5 Mavericks *vs* wait-and-see firms

It is generally considered that established firms find it extremely difficult to pursue a rapidly evolving “disruptive technology” that is not yet mature enough to serve their current customers (Christensen, 1997). Considering the development of new safer alternative substitutes such as those pushed by regulation, these are radically new technologies which modify the key factors for success. Not every firm perceives them as a strategic opportunity and not every firm will demonstrate a high entrepreneurial orientation, measured by amounts of innovativeness, risk taking and proactiveness (Covin and Slevin, 1989). In this regard, green entrepreneurs represent crucial change agents able to play such a proactive role in spite of high uncertainty associated with the future technology option. The category of green entrepreneurs is itself heterogeneous and different typologies have been proposed in the management literature to identify multiple ideal types (Walley and Taylor, 2002; Neumeyer and Santos, 2018, among others). For the sake of consistency, we propose to qualify as *mavericks* those firms that take the risk early of developing a cleaner but immature substitute. Their distinctive feature is that they take the risk of pioneering by experimenting with a technology disruption which may occur when, despite its inferior performance in focal attributes, the new technology manages to displace the mainstream technology from the mainstream market (Christensen, 1997; Adner, 2002). At the other extreme are those opportunist and risk-adverse firms characterized by a wait-and-see attitude towards the regulatory threat until the new disruptive technology has been introduced by rivals and is widely diffused in the market before switching to it. We call them *wait-and-see firms*. With regard to these risk-taking attitudes and green orientations, there is a continuum of firm profiles ranging from mavericks to opportunistic followers and laggards. In the formal model, this continuum is represented by distinct knowledge and adoption thresholds.

3. Model

3.1 Agent-based modeling

This article uses agent-based modeling as a basis for exploring a key policy dilemma confronting ambitious and stringent environmental policy with other conflicting public interest dimensions, ranging from competition distortions to relocation, job loss and adverse trade effects. Agent-based modeling is a relevant tool for investigating economic policy measures, in particular environmental policy (Heckbert et al., 2010), and for providing policy recommendations in complex environments (Farmer and Foley, 2009). It is a strongly micro-founded approach that considers the emergence of patterns at aggregated levels of analysis that originates from the micro-interaction of agents, who follow particular behavioral rules and may be constrained in their choices by various institutional arrangements (Dawid and Neugart, 2011). Such economic models should be able to give insight into how environmental policies could affect the broad characteristics of economic performance, by exploring how the economy is likely to react under different scenarios. We extend the Brouillat et al. (2018) model by adding new assumptions and features, in order to examine with a finer-grained analysis issues that are recurrent in the transition to a low-carbon economy. Before presenting and discussing the simulation results, we present the basic structure of the model. We will not provide a full account of the model. The reader may refer to Brouillat et al. (2018) for a detailed description of the formal model. We will rather focus on the changes and improvements that have been made to conduct the present study.

3.2 Product-related technologies

We consider the interactions of suppliers and clients on the market of substances used for epoxy resins for food containers. Suppliers search for a dominant position in the market through innovation. They develop, produce, and sell products depicted as multi-characteristic technologies described by four attributes: technical quality, productive efficiency, toxicity, and environmental risk of bioaccumulation. The potential for improvement through innovation assigned to each attribute is defined by its initial value and its outer limit. Two types of product-related technologies that radically differ in their attributes are considered: bisphenols, called technology T1, and bio-based substitution solutions, called technology T2. T2 is a bio-based technology, so its initial values and outer limits regarding toxicity and environmental risk of bioaccumulation are better than the values of the conventional technology T1. However, T2 is an emerging technology and is initially more expensive and lower performing in terms of technical quality than T1.

3.3 Technology portfolio

Only T1 is available at the start of the simulation, but suppliers are assumed to accumulate knowledge about T2 through an R&D watch in order to introduce into the market products based on T2 with competitive prices and technical quality. Thus, in each period, suppliers examine the possibility of introducing T2 into the market through a three-step process depicted in Table 1.

Step 1	Each supplier compares its cumulated stock of knowledge on T2 derived from the supplier's technological watch with a firm-specific threshold. If the knowledge stock is above the threshold, then the cumulated knowledge is considered as sufficient to adopt T2 and the supplier moves to the second step; if not, the supplier decides not to adopt T2 in the current period.
Step 2	The supplier compares the total market share of T2 with a firm-specific threshold. If the market share is above the threshold, then the supplier considers that T2 has diffused sufficiently in the market and moves to the third step; if not, the supplier decides not to adopt T2 in the current period.
Step 3	The supplier compares its budget with the switching costs related to T2. If the budget is sufficient to bear the switching costs, then the supplier adopts T2; if not, it decides not to adopt T2 in the current period.

Table 1 – Decision process for T2 adoption

Regarding this adoption procedure, we consider two types of suppliers: *wait-and-see suppliers* and *mavericks* as defined in section 2.5. Formally, while wait-and-see suppliers follow the whole three-step procedure, mavericks move directly from step 1 to step 3 by skipping step 2. In other words, contrary to regular suppliers, mavericks would take the risk of being a pioneer in T2.[8]

In each subsequent period, suppliers that decide to adopt T2 will have to choose between continuing to produce and sell T1 or abandoning T1 and focusing only on the development of T2. To make this decision, each supplier calculates the share held by T2 in its total turnover and compares it with a firm-specific threshold; the higher the share or the lower the threshold is, the higher the likelihood of betting only on T2 and abandoning T1.[9]

3.4 Innovation, production costs and pricing strategy

Each period, each supplier allocates a certain proportion of its budget to R&D in order to accumulate technological knowledge and to improve product performance in its portfolio. The R&D budget is split into two parts: the first is dedicated to the improvement of T1 and the second is assigned to the development of T2. Suppliers that have decided to abandon T1 allocate their entire R&D budget to the development of T2.

R&D may lead suppliers to improve the technical quality of products or to decrease toxicity and environmental risk of bioaccumulation. This quality effect of innovation is costly, leading to a price premium. However, R&D may also decrease production costs thanks to improvements in productive efficiency, enabling suppliers to offer lower prices. Because the quality effect and the efficiency effect of innovation are independent, the total net effect on cost may be positive or negative and will depend on the interactions among suppliers, users, and technology.

The price is deduced from production costs by applying a mark-up rate that increases with the individual market share of the supplier and with market concentration, so that it takes into account both the individual market power of the supplier and the market power for an industry as a whole.

Profits are obtained by subtracting production and R&D costs from turnover. The budget of the supplier is determined by the residual budget from the previous period and the profits.

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[8] By definition, it is obviously less likely for a firm to be a maverick. Thus, we randomly assign to each supplier the wait-and-see/maverick feature with a lower probability associated with the latter feature.

[9] We assume that the decision to abandon T1 is final in the sense that the firm cannot go back and adopt the technology again.

3.5 Exit and entry

Suppliers with a negative budget go bankrupt and leave the market. New competitors enter the market with probabilities positively dependent on unexploited technological potential. The technology portfolio and the product characteristics of the new entrant are fixed by copying an incumbent. The entrant is assumed to have a specific absorptive capacity that enables it to overperform or inversely underperform in comparison with the imitated incumbent.

3.6 Product purchase

Clients buy and use one type of product (T1 or T2) in their production processes with the objective of finding the most satisfactory product consistent with their preferences and with their techno-economic constraints.[10] The purchasing process of clients is subject to bounded rationality in the sense that clients' decisions rely on satisfying rules based on their own perceptions of product attributes, leading to possible sub-optimal choices.

At the very first period of the simulation run, each client selects a product through the four-step process depicted in Table 2.

Step 1	The client randomly chooses one product characteristic with probabilities proportional to the client-specific preferences in terms of technical quality of products, price, toxicity, and environmental risk of bioaccumulation.
Step 2	The client scans all the products marketed by each supplier and gives them a score. The score of a product is positively dependent on its market share (bandwagon effect) and its performance in the selected characteristic in Step 1. This performance is imperfectly evaluated by the client; it results from a random draw in a uniform distribution centered on its actual value.
Step 3	The client randomly selects one product. The probability of a product being chosen is proportional to its score calculated in Step 2.
Step 4	Each client is characterized by a reserve price and a minimum technical quality requirement reflecting its specific economic and technical constraints. If the selected product does not satisfy one of these constraints, it is discarded and the client goes back to Step 3 to select another product. If there is no product that satisfies these constraints, the client does not buy and own any product during the period.

Table 2 – Decision process for product choice

In the subsequent periods, the client can choose to keep or to leave its current supplier through the two-step process presented in Table 3.

Step 1	The client randomly chooses one product characteristic with probabilities proportional to the client-specific preferences in terms of technical quality of products, price, toxicity, and environmental risk of bioaccumulation.
Step 2	The client compares the performance of its current product in the selected characteristic in Step 1 with the best industry performance achieved. The latter is weighted by a coefficient allowing a certain zone of tolerance according to which a client may accept variation within a range of performances. If the performance of its current product is below the weighted best industry performance, the client leaves its current supplier and chooses another one through the purchase procedure; otherwise, the client keeps the same supplier.

Table 3 – Decision process for keeping or leaving supplier

[10] Each client is assumed to use one single product at the same time and to renew its purchase every period.

3.7 Regulation mechanisms

We focus on one main mechanism underlying REACH, namely the authorization process. The authorization process is modeled as a sequential checking procedure based on a sunset date associated with revision dates and target thresholds. When the current period is the sunset date, the public agency compares the average technical performance and the average productive efficiency of T2 with the techno-economic performance targets. If the average technical performance *and* the average efficiency of T2 are above the performance targets, bio-based substitution solutions are considered by the public agency as economically and technically viable and T1 is prohibited after the cutoff date. Conversely, if T2 does not reach the targets, an authorization to keep on developing and marketing T1 after the sunset date and until the next revision date can be granted to suppliers who can prove that they carried out serious analyses of alternatives. More precisely, the authorization is granted only if the supplier's budget allocated to R&D watch on T2 exceeds the average R&D watch performed in the industry weighted by a coefficient reflecting the severity of the regulation. At the revision date, a similar sequential check is done.

In view of the foregoing, strict enforcement of the authorization would force some suppliers to leave the market. In the event of a T1 prohibition, every supplier with only T1 in its portfolio would be systematically prevented from accessing the market, and if T1 is not yet prohibited, every supplier with insufficient R&D watch on T2 could no longer sell its product. As shown in Section 2.2, such strict enforcement could lead to damaging economic side effects by pushing non-compliant firms out of the market. Thus, the authorization enforcement decision will not just be about environmental and health concerns. As mentioned in Section 2.3, we assume that negotiation and lobbying would result in a political compromise modeled as a fixed threshold, called *MinSuppliers* depicting the lower limit on the current number of suppliers, that is economically, politically and socially accepted by stakeholders. The authorization enforcement decision is the following: the regulation is implemented (T1 prohibition or R&D watch checking) only if after the cutoff date the number of remaining suppliers exceeds *MinSuppliers*. If not, the authorization process is postponed to the next revision date.

By introducing the threat of a T1 prohibition, the authorization process puts pressure on suppliers and clients to focus on bio-based alternatives. The intensity of this pressure inherently depends on the extent of the threat. It is represented in the model by the firm-specific variable *Threat* computed for agent *i* at period *t* with the following equation:

$$Threat_{i,t} = Target_t . Timing_t . Enforce_t . Percept_i$$

Target, *Timing*, *Enforce* and *Percept* are depicted in Table 4. These variables reflect the different facets of the threat as it may be perceived and assessed by agents. *Threat* varies between 0 and 1 and the higher its value, the higher the extent of the threat.

Description	Computation
Target: extent of the threat with respect to techno-economic performance targets. The closer the average performances of T2 to the performance target thresholds, the higher the extent of the threat.[11]	$Target_t = min\left(\frac{AvX_{t-1}}{X^*}; \frac{AvEff_{t-1}}{Eff^*}\right)$ with *AvX* and *AvEff* respectively the average technical performance and the average productive efficiency of T2, and *X** and *Eff** the techno-economic performance target thresholds of the regulation.

Timing: extent of the threat with respect to time constraints.
The closer the sunset (or revision) date, the higher the extent of the threat.[12]
	if $t \leq T_{sunset}$:
	$Timing_t = \frac{t}{T_{sunset}}$
	if $t > T_{sunset}$:
	$Timing_t = 1 - \frac{T_{revision} - t}{\Delta T_{revision}}$
	with T_{sunset} the sunset date, $T_{revision}$ the revision date and $\Delta T_{revision}$ the time gap between two successive revisions.

Enforce: extent of the threat with respect to the enforcement or the postponement of the regulation (T1 prohibition and R&D watch checking). The greater the number of postponements of the regulation, the lower the extent of the threat.[13]	$Enforce_t = 1 - \frac{Post_{t-1}}{maxPost}$ with *Post* the cumulated number of postponements of the regulation and *maxPost* the maximum admissible number of postponements over the simulation run.
Percept: extent of the threat with respect to the individual sensitivity of the agent. The higher the value for *Percept*, the more the agent perceives the T1 prohibition as a credible threat.	$Percept_i$: firm-specific parameter drawn from a uniform distribution with values between 0 and 1.

Table 4 – Explanatory variables for *Threat*

The threat of a T1 prohibition introduced by the authorization process would impact suppliers upstream through the allocation of R&D expenditures between T1 and T2 (see Section 3.4). The share of the global R&D budget allocated to T1 is now weighted by a factor (1 – *Threat*). The possibility of a T1 prohibition would thus encourage suppliers to revise their allocation of R&D expenditures in favor of T2 and to the detriment of T1. The threat of a T1 prohibition would also impact suppliers downstream through the decision to market T2 or not. In step 2 of the sequential decision process driving the adoption of T2 (see Table 1), suppliers now compare the total market share of T2 weighted by a factor (1 + *Threat*) with their specific threshold. This would encourage suppliers to revise their appraisal of the actual diffusion of bio-based substitution solutions and push them to market T2 in turn. According to these changes, the higher the extent of the threat, the greater the inducement for suppliers to reorient their R&D activities toward T2, and the faster they will develop and market T2.

The threat of a T1 prohibition introduced by the authorization process can be seen by clients using T1 as the threat of a radical change in their factors of production and the possibility of having to find a new supplier. As a result, clients are closely associated with regulatory requirements and the technology portfolio held by suppliers matters in their decisions. Symmetrically to suppliers, two decision processes are affected. First, in the four-step purchase procedure (see Table 2), the score functions (step 2) given to the product of suppliers holding a portfolio without T2 are now weighted

[11] *Target* ∈ [0; 1] and is limited to 1 in the case of postponement of T1 prohibition.

[12] *Timing* ∈ [0; 1].

[13] *Enforce* ∈ [0; 1].

by a factor (1 - *Threat*). Second, the two-step decision procedure made by a client to keep the same supplier or to switch to another supplier (see Table 3) is now preceded by a prior step for clients whose supplier does not have T2 in its portfolio. This prior step consists of leaving the supplier with a probability given by *Threat*. According to these changes, the higher the extent of the threat, the more clients will select and keep a supplier with T2 in its portfolio.

4. Results

4.1 Experimental set-up

We parametrize the model by using the calibration of Brouillat et al. (2018). Given the recurring criticism of agent-based modeling due to its lack of a sound empirical grounding (Fagiolo, 2007; Fagiolo et al., 2007; Lamperti, 2018; Gallegati and Richiardi, 2009), Brouillat et al. collected and used empirical data on the characteristics of production and demand of bisphenols. In particular, parameters capturing product characteristics were calibrated based on data gathered by INERIS (2010, 2014) in order to account for the differences between bisphenol-based materials and bio-based substitution materials, as empirically observed. A sensitivity analysis was performed by the authors to validate the model.

In the present modeling exercise, we focus on the impact of policy features and policy enforcement on the transition from bisphenol-based technologies to bio-based substitution technologies. We ran simulations with 250 periods each to allow sufficient time for evolutionary processes to be implemented. The policy is depicted by three parameters: a timing index (*Time*), a stringency index (*Stringency*) and *MinSuppliers*. *Time* is a synthetic index gathering the two timing parameters T_{sunset} and $\Delta T_{revision}$. Its value is between 1 and 10, 1 reflecting the longest timing and 10 the shortest (see Table A1 in appendix). *Stringency* is also a synthetic index combining the three parameters that reflect the severity of the regulation: the two techno-economic performance target thresholds, *X** and *Eff**, and α_{watch}, a parameter reflecting the severity of the regulation on R&D watch. The value of *Stringency* is between 1 and 10, 1 reflecting the lowest stringency level and 10 the highest (see Table A2 in appendix). As regards *MinSuppliers*, we assume that its minimum value is fixed to 2. In fact, when negotiating policy enforcement, one can reasonably assume that stakeholders would at least avoid a monopoly situation. Its maximum value is fixed to 10, which is the initial number of suppliers at the start of each simulation run.[14]

4.2 Hierarchy of policy features

First, we perform our analysis of the model on policy parameters based on a set of simulations carried out with a Monte Carlo procedure. We run 10,000 simulations with a random setting of the values of the parameters in order to generate a large number of possible outcomes covering a diversified subset of the parameter space. For each of the 10,000 simulations, *Time* and *Stringency* are randomly chosen between 1 and 10 and *MinSuppliers* is randomly chosen between 2 and 10. We process results with regression trees. A regression tree (Venables and Ripley, 1999) establishes a hierarchy between independent variables using their contributions to the overall fit (R^2) of the regression. Dependent variables are the frequency of T1 prohibition (Figure 1), the time period the

[14] At the start of a simulation run, we consider a population of 10 suppliers facing a population of 200 clients to account for the prevailing industry structure in the bisphenols market.

prohibition occurs (Figure 2) and the inverse Herfindahl–Hirschman index of concentration[15] (Figure 3). Independent variables are the three policy parameters *Time*, *Stringency* and *MinSuppliers*. The tree gives a hierarchical sequence of conditions on these parameters: the higher the role of a condition in the classification of the observed case, the higher its status on the tree. For each condition, the left branch shows the cases for which the condition is true and the right branch indicates cases compatible with the complementary condition. The two numbers at the leaves of the trees are the expected value of the dependent variable and the number *n* of observations for which the condition(s) on the parameter(s) is (are) satisfied.[16]

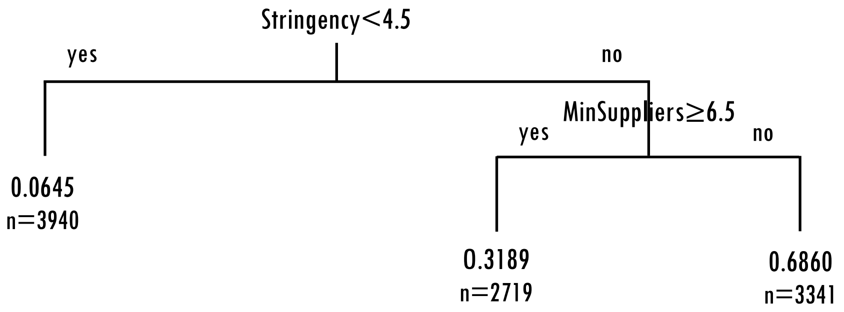

Figure 1 – Regression tree of T1 prohibition frequency

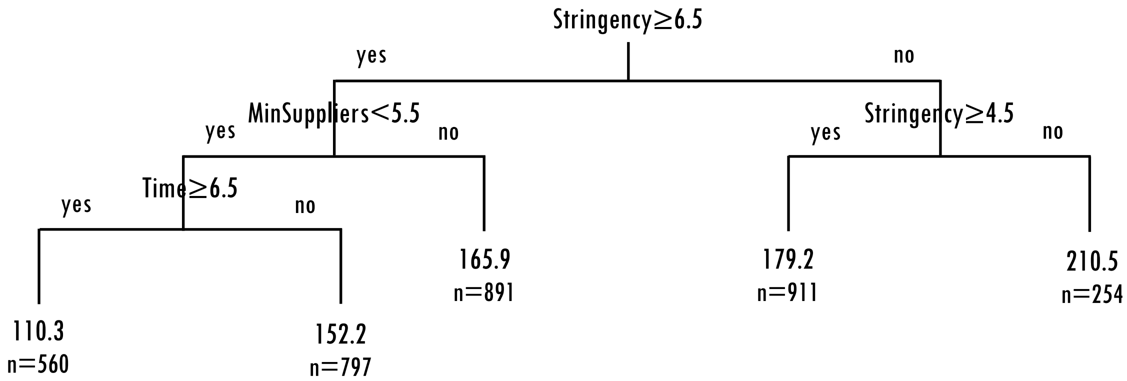

Figure 2 – Regression tree of prohibition time period

[15] The inverse Herfindahl–Hirschman index of concentration can range from 1 to N (N is the number of firms in the market), moving from a single monopolistic producer to a large number of very small firms. Decreases in the index generally indicate a decrease in competition and an increase in market power, whereas increases indicate the opposite.

[16] For instance in Figure 1, on the left branch of the tree, we have all observations for which *Stringency*<4.5. On the right branch, we have all observations for which *Stringency*≥4.5. There are *n*=2,719 observations over 10,000 for which *Stringency*≥4.5 and *MinSuppliers*≥6.5, and in this case the frequency of T1 prohibition is 31.89%.

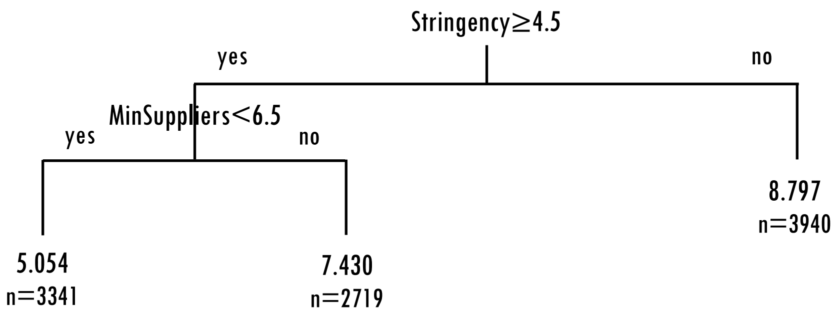

Figure 3 – Regression tree of inverse Herfindahl–Hirschman index of concentration

As regards the hierarchy between independent variables, trees exhibit that the degree of stringency is the most determining policy feature in technological transition. In particular, in Figure 1 and 2, one can note that, if the policy is not sufficiently severe (*Stringency*<4.5), the chances of T1 prohibition are very tenuous (6.45%), and in the few cases it occurs, it does so late (*t*=210.5).

The question of policy enforcement, depicted by *MinSupplier*s*,* appears to be of secondary importance. In other words, to be effective, the regulation must first and foremost be sufficiently severe, and then the question of its enforcement arises. Still, this question remains decisive since, depending on strict or lax policy enforcement, the chances of T1 being banned vary by twice as much (31.89% vs. 68.60%). Thus, the highest frequency of T1 prohibition (68.60%) is observed when the stringency index is sufficiently high and the threshold of suppliers is sufficiently low (*Stringency*≥4.5 and *MinSuppliers*<6.5). Such a policy configuration also leads to faster prohibition (Figure 2). The earliest T1 prohibition is observed when the strict enforcement of the severe regulation (*Stringency*≥6.5 and *MinSuppliers*<5.5) is backed by a short timing (*Time*≥6.5). However, by pushing non-compliant firms out of the market, this strict and severe regulatory framework would result in a significant increase in market concentration (Figure 3).

Lastly, it may be noted that the timing of the regulation is the least decisive criterion, since *Time* only appears on one tree, in third place. This does not mean that it is a negligible aspect, but simply that its relative importance is lower than that of the other parameters. In fact, regression trees just give a first insight into the impact of policy features and policy enforcement on technological transition. They must be accompanied by a more accurate study of the possible combinations of the three parameters, especially in cases of relatively stringent regulations, since it is in those cases that the technological transition is the most likely to take place, as we have just seen. Indeed, trees merely indicate that regulation must be sufficiently severe, its enforcement sufficiently strict and its timing sufficiently short for T1 prohibition to have the best chance of taking place quickly. However, this does not mean that the combination of the most severe regulation with the strictest enforcement and the shortest timing would necessarily yield the highest chances of quick T1 prohibition. Actually, it does not, as we will see.

4.3 The combined effects of stringency, timing and enforcement thresholds

We now investigate the combined effects of stringency, timing and enforcement thresholds. We perform several experiments varying the degree of stringency, the timespan and the minimum number of suppliers acceptable when enforcing regulation. *Stringency* varies from 1 to 10. Three enforcement thresholds are considered: strict enforcement (*MinSuppliers*=2), lenient enforcement (*MinSuppliers*=6) and lax enforcement (*MinSuppliers*=10). Three timing levels are also considered: short timing (*Time*=10), medium timing (*Time*=5) and long timing (*Time*=1).[17] Table 5 recaps the examined cases.

Enforcement threshold	Strict	*Minsuppliers*=2
	Lenient	*MinSuppliers*=6
	Lax	*MinSuppliers*=10
Timing	Short	*Time*=10
	Medium	*Time*=5
	Long	*Time*=1

Table 5 – Examined enforcement thresholds and timing levels

Figure 4 displays the frequency of T1 bans measured at the end of the simulation period (time t=250) according to varying degrees of stringency (horizontal axis), timing and enforcement thresholds. As we raise the degree of stringency from 1 to 10, we can observe that the frequency of banning T1 increases and automatically increases T2's market share. It is confirmed that a level of severity equal to or larger than 4 is needed to guarantee a great likelihood of transition. However, as already mentioned, the combination of the most severe regulation (*Stringency*=10) with the strictest enforcement (*MinSuppliers*=2) and the shortest timing (*Time*=10) would not necessarily lead to the highest frequency of banning T1. On this point and complementary to results displayed by regression trees in the previous section, two new striking results can be highlighted. As we look at the solid black line in Figure 4, we can observe how the frequency of T1 ban increases as stringency rises from 1 to 6, reaches a maximum at around 90% before dropping as stringency continues to rise from 6 to 10, finally standing at 76%. We are facing an apparently counterintuitive result: as the degree of stringency rises above a certain level, the likelihood of prohibiting T1 decreases and concomitantly the likelihood of transition.

[17] The values presented in this section are obtained through the following procedure: for each considered level of *MinSuppliers* (2, 6 and 10) and *Time* (1, 5 and 10), we perform a set of 10,000 simulations with a random setting of the value for *Stringency*. Then, for each set of simulations, we gather the simulations with the same value for *Stringency* and we calculate the frequency of T1 bans observed over those cases. T-tests have been systematically carried out to check for significant statistical differences between values (significant p-value at the 1% level).

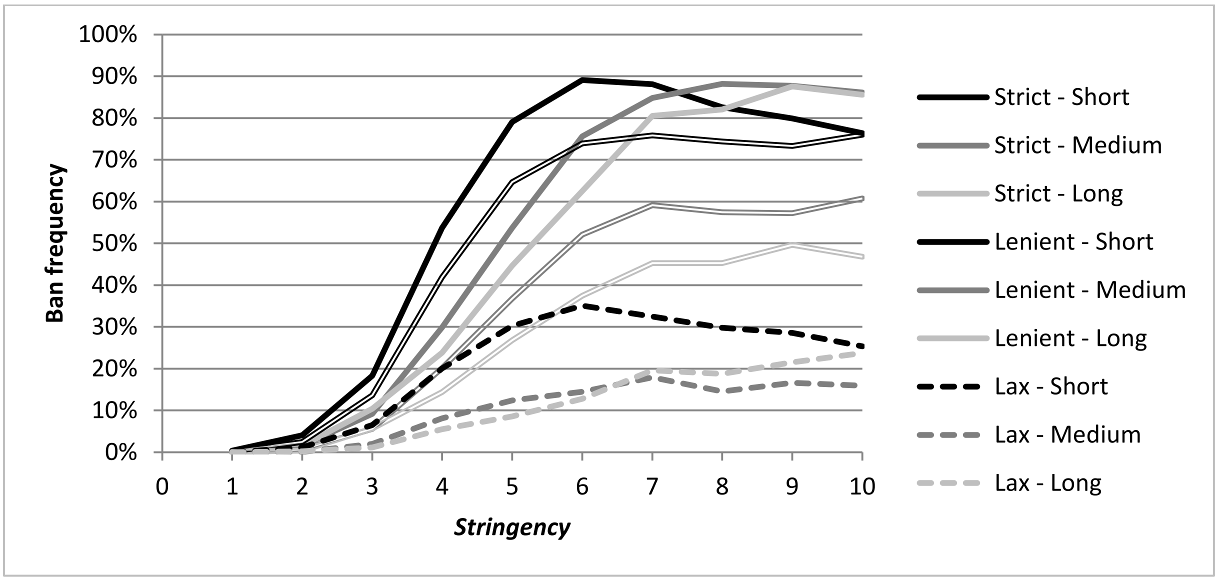

Figure 4 – Frequency of T1 bans according to varying degrees of stringency, timing and enforcement thresholds

The explanation rests on the pressure mechanism that makes the authorization to produce, market and use harmful substances conditional upon the ongoing industry performance. Above a certain threshold, as stringency increases and the authorities stick to the letter of the regulation, the pressure placed on firms is so intense that authorization permits are not granted and many firms have to exit the market. Among these firms are the critical players we have called mavericks, which are driven out too early from the market. The regulatory pressure forces green pioneers to prematurely end accumulating knowledge on T2, whereas when ready they would take the risk of marketing the technology even if no current demand exists. But in order for T1 to be likely to be prohibited, there must be at least one firm with T2 in its portfolio, and only a maverick can adopt T2 in spite of a lack of demand, contrary to other firms with a wait-and-see attitude. If all the mavericks are pushed out of the market, the lower diversity of firms' strategies will lock the system into T1 until technological opportunities are exhausted and entry of new firms is hindered, so that ultimately a tight oligopolistic situation (often a duopoly) ends up as a stable market configuration. Thanks to their sizeable profits, the surviving wait-and-see firms have substantial R&D watch budgets, guaranteeing them the authorization permit. They accumulate knowledge on T2 but they have no intention of taking the risk of being the first mover in that technology. As clearly emerges when looking at the other two solid lines in Figure 4, weaker timing constraints allow a higher likelihood of transition due to a higher likelihood of T1 prohibition, confirming that a compromise between severity and timing must be found since otherwise mavericks may be prematurely squeezed out.

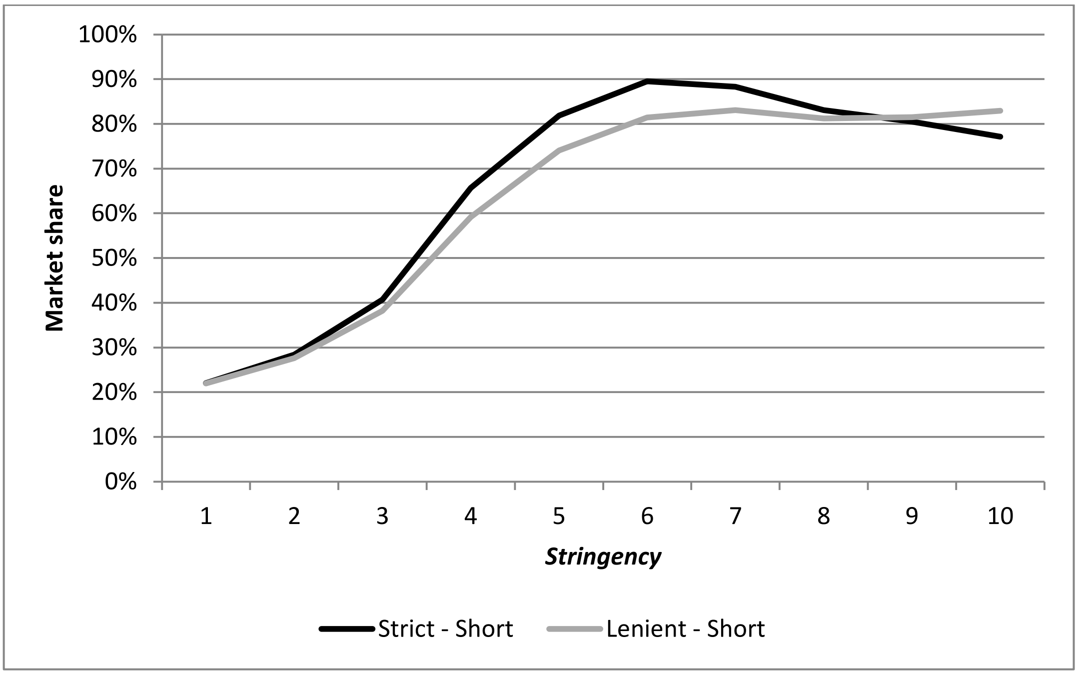

Figure 5 – Market share of T2 according to varying degrees of stringency, timing and enforcement thresholds[18]

The second striking result appears when comparing different enforcement thresholds given very strict targets (*Stringency*=10). As displayed in Table 6 and in Figure 4, when stringency is high and timing tight, the likelihood of T1 prohibition (ban frequency) is the same (76%), whether enforcement is strict or lenient. However, if we compare the two situations in terms of market structure, we face two different configurations: market concentration as measured by the inverse Herfindahl –Hirschman index is significantly lower (respectively 3.27 *vs* 5.57), and the number of surviving firms is significantly higher (respectively 3.38 *vs* 5.96). Also, in terms of likelihood of transition, the system under lenient enforcement performs better, as indicated by the T2 market share indicator, which amounts to almost 83% against 77% in case of strict enforcement (see Figure 5). This can be explained by looking at the number of surviving firms when no ban on T1 occurs during the whole simulation period: it is significantly lower in case of strict enforcement (2.3) than lenient enforcement (6.79). As performance targets for T2 are very high and the pressure maximum, some firms may experience a premature exit, an event that leads to the removal of mavericks, as already discussed. Note that by loosening the timing pressure (see Table 7) we observe a sharp increase in the ban frequency (86% rather than 76%) and T2 market share (86% rather than 77%) because of the presence of a maverick whose risky behavior is to adopt T2 in its portfolio, thus paving the way for a likely prohibition of T1.

[18] A *t*-test has been carried out to check for significant statistical differences between the two configurations under scrutiny. No significant differences exist for cases of stringency level equal to 1, 2, 3, 8 and 9. Significant differences occur for the other cases (i.e. stringency levels from 4 to 7 and 10).

Values at t=250	Enforcement threshold		
	Strict	Lenient	Lax
T1 ban frequency	76.3% *(n.s)*	76.0%	25.3% *(***)*
Inverse Herfindahl – Hirschman index	3.27 *(***)*	5.57	8.69 *(***)*
Average number of competitors	3.38 *(***)*	5.96	9.66 *(***)*
Average number of competitors when no T1 ban	2.3 *(***)*	6.79	10.8 *(***)*
T2 market share	77.1% *(***)*	82.9%	42.7% *(***)*

Table 6 – Comparison of indicators at time t=250 for different enforcement thresholds in scenarios with high stringency (*Stringency*=10) and short timing (*Time*=10)[19]

Values at t=250	Enforcement threshold		
	Strict	Lenient	Lax
T1 ban frequency	86% *(***)*	60.7%	15.9% *(***)*
Inverse Herfindahl – Hirschman index	3.67 *(***)*	5.71	8.86 *(***)*
Average number of competitors	3.84 *(***)*	6.24	9.90 *(***)*
Average number of competitors when no T1 ban	2.9 *(***)*	7.19	10.57 *(***)*
T2 market share	86.6% *(***)*	71.2%	36.5% *(***)*

Table 7 – Comparison of indicators at time t=250 for different enforcement thresholds in scenarios with high stringency (*Stringency*=10) and medium timing (*Time*=5)[20]

In terms of policy implications, opting for a very stringent regulation in terms of strict performance targets and short timing should go together with making concessions on enforcement and tolerating a number of market exits that is not too high. Under this configuration the system performs better overall, since transition is more likely to happen and fewer firms are evicted from the market. From a reverse angle, if authorities are keen to strictly apply the regulation and prepared to face higher market concentration, then they should release the degree of stringency in order to enhance the prospects of prohibiting T1 and switching to T2. Note, however, that too lax an enforcement leads to the regulatory threat being discredited, as illustrated by all the indicators in Table 7 for an enforcement threshold of 10 firms. In that case, the likelihood of T1 being prohibited is rather low (15.9%), generating, on average, low diffusion of T2 (36.5%) in spite of low market concentration (8.86). This is because the credibility gap is so high that firms reduce their innovative efforts, thus reducing the likelihood of coping with regulation, and so on, initiating a vicious circle hindering any hope of transition.

5. Discussion

In this article we have examined the combined effect of policy stringency, timing and enforcement thresholds upon industrial dynamics, when perception by firms of regulatory stringency is updated when they observe recurrent postponements of a product ban for competitiveness reasons (for the sake of minimizing side-effects). Our focus in this article was on the impact of *implementation gaps*

[19] A *t*-test has been carried out to check for significant statistical differences between values for the lenient and the strict scenario on the one hand and between the lenient and the lax scenario on the other hand. (***) represents significant *p*-value at the 1% level. (n.s.) stands for 'not significant'.

[20] See footnote 19.

observed in environmental regulation on the perceived strictness of the regulatory regime and ultimately on the likelihood of a successful transition to cleaner technologies. Contrary to Brouillat et al. (2018), enforcement is not mechanically applied but instead is conditional upon exceeding thresholds governing firm survival or involuntary market exit. When stringency is above a certain level -in terms of performance objectives and timing- and enforcement sticks to the letter, thus being very strict, results in terms of the product ban and cleaner technology transition are not efficient. When stringency is intermediate and enforcement is strict, technology transition is achieved with lower side-effects. However, when stringency is high, it becomes efficient in loosening the pressure when the regulation is implemented in order to regain credibility. This result contrasts with other findings in the literature, where technology transition depends only upon stringency (Arfaoui et al., 2014; Brouillat et al., 2018).[21] But this result is more in line with empirical evidence showing that firms would perceive strict noncompliance penalties in the event of failure to innovate as a strong disincentive (Ashford et al., 1985). By adopting a sensible enforcement posture (a *"fail-soft" approach*, as coined by Ashford et al., 1985, p.427), the regulatory agency does not unduly penalize a good-faith firm which attempts to innovate to meet the required limits, yet fails.

The lack of efficiency resulting from coupling very strict objectives and full enforcement is caused by the fact that the cut-off penalty falls prior to the advent of mature mavericks. Indeed, strict implementation through frequent monitoring jeopardizes the time required by firms that take the risk early of developing a cleaner but immature substitute (the so-called mavericks). In particular, in the early phase of the dynamics, when no cleaner alternative is commercialized on the market, the authorization is granted only if the supplier's budget allocated to the R&D watch on substitutes is above a certain level (see §3.2). The only way to make the conventional technology likely to be prohibited depends on the existence of at least one supplier having a substitute in its portfolio, and ready to be a pioneer no matter how small the market is for that substitute. But the problem is that a strong sequential check on R&D watch unduly penalizes these mavericks and contributes to embedding the established firms developing the conventional technology, thus causing a lock-in situation. If it is possible to loosen the pressure so that mavericks have enough time to develop, the regulator could make the cut-off penalty dependent on actual diversity but not dependent upon the risk of evicting too many noncompliant firms. This would avoid an overly faithful implementation which would be harmful to the diversity of strategies, while still affording enough credibility to the regulatory threat and maintaining pressure on firms to keep developing cleaner alternatives. This need to ease the pressure, which is likely to be demanded in practice because of the likely negative side-effects attributed to ambitious environmental policy, should rather be considered in the light of the principle that "concentration crowds out diversity" (Jonard & Yildizoglu, 1999).

Even with strict enforcement, the lack of efficiency of a strong coupling between stringency and enforcement could be overcome by making concessions in the degree of stringency in terms of performance standards and timing. In other words, if the regulator allows a significant drop in the number of competitors due to strict enforcement, negotiating parties should compromise in order to reach a less severe agreement, thus allowing enough diversity of strategies. However, there are limits to such compromises since the loss of credibility resulting from excessively high

[21] The three models are different versions of the same computational structure. However, in the perspective of a cumulative multi-stage simulation work, we believe that the differences, particularly for the use and hence the kind of results, are more relevant than the similarities in the underlining code, and hence the substantial "recycling" of the code in a different article is not only justified, but even desirable.

implementation gaps leads to lower innovating efforts, thus decreasing the probability of applying the cut-off sanction, and thus further losing credibility owing to that very postponement, etc. In some cases of coupling, we therefore end up with an inverted-U relationship between the credibility of the regulator's threat and the stringency of environmental policy: too lax or too severe a regulation is associated with low credibility and low innovation, while high credibility and highly sustained innovation comes with an intermediate level of stringency.

In all cases, maintaining mavericks in the early phase of the sequential monitoring process is crucial to help foster technology transition. Special attention to the profile of these green pioneering firms should thus be considered. From an evolutionary perspective, variety, in the form of differences in R&D strengths and strategies,[22] is crucial to innovation (Metcalfe, 1995). Diversity in behavior is particularly prominent between leading and marginal competitors and a substantial body of evidence shows that leading incumbents prefer a different path of innovation to that chosen by challengers. According to Dorfman (1987, p.240), "*Leading companies* […] *generally use technology as a means of reinforcing their position without changing the fundamental rules of the game* […] *Because it may disrupt the nature of competition in a given industry, a new technology which modifies the key factors for success tends to be perceived as a strategic opportunity by marginal competitors, and as a threat by the leading competitors, even if they are the ones which developed the new technology*." In order to support these green marginal pioneers, innovation policies targeted at green entrepreneurs would need to be coordinated with environmental policy in the early phase of the dynamics. This result corroborates the strategic niche management (SNM) approach which focuses on the creation of technological niches described as "the creation, development and controlled phase-out of protected spaces for the development and use of promising technologies by means of experimentation, with the aim of (1) learning about the desirability of the new technology and (2) enhancing the further development and the rate of application of the new technology" (Kemp et al., 1998, p.186). Thus, paralleling the monitoring process, public support directed towards green mavericks is needed, as already emphasized by Mazzucato (2015) who provides evidence on the crucial role of federally funded R&D research labs for the development of green start-ups.

These results also have implications for competition policy. They not only show how stringent environmental policies have direct effects on levels of competition, but also that, for mavericks, it is of great importance whether enforcement is strict or lenient and aligned with the degree of policy stringency, that is, when the product ban is effectively applied. Antitrust policies which aim is to reduce a high level of concentration in the market should pay attention to the capacity of the product ban to help the environmental objectives properly. Moreover, in industries characterized by competitors with different technologies and resources, competition is based on product attributes and performance as well as price. Hence, an important impact on the performance dimension of competition stems from whether implementation gaps are high or low between stringency requirements and enforcement is real but conditional. Thus, both environmental policies and competition policies should further consider maintaining multiple sources of variation and innovation.

[22] Variety is crucial together with selection which allows particular R&D strengths and strategies to survive or die. "*The distinctive feature of any evolutionary model is the role which variety in behavior plays in driving a selection process to alter the relative importance of the different behaviors*." (Metcalfe, 1994, p.936)

In this model we assumed a fixed posture during the whole simulation period for the agency responsible for checking the process. An alternative formulation would be to assume that the agency learns from progress in development within the regulated industry. In doing so we would better account for the process whereby public authorities learn and adjust their behavior in response to what is learned. As Nelson and Winter (1982) have already underlined in the case of clean air regulation, many public policy issues are complex, the nature of the problems and the options not well understood, and the values at stake far from transparent. Beliefs about the nature of the problem play an important role at several stages, from diagnosis to evaluation of the policy problem (Nelson and Winter, 1982, p.378[23]). Additionally, the implementation of a policy is subject to diverging beliefs, as it both generates new information about what works and what doesn't, and involves solving conflicts of interest among the potential beneficiaries and losers. Following such a perspective, more attention needs to be given to the joint endogeneity of innovation and policy (Carrion-Flores & Innes, 2010). The regulatory capture argument based on testing of strength and bargaining that are part of the political process makes incumbents more likely to lobby for policies that are less conducive to innovation. Yet, an awareness that environmental policy stringency coupled with the right enforcement affects perceptions, and expectations about future regulation are an important point to consider when designing policies under conditions of genuine or *fabricated* uncertainty,-as coined by Henry (2013). A strong emphasis should be placed on studies that attempt to assess the scientific evidence about environment or health effects and the evolving state of the technological arts. Indeed, such studies are expected to present arguments that rationally persuade people that one policy is better than another, in terms of values that are widely accepted and that are viewed as applying to society as a whole rather than to a particular group (Nelson and Winter, 1982). These considerations become particularly salient for current topical issues such as those raised by pesticides or endocrine disruptors.

6. Conclusion

In this article, we have studied the impact of the *implementation gaps* observed in environmental regulation upon the perceived strictness of the regulatory regime and ultimately on the likelihood of a successful transition to cleaner technologies. We have built upon an existing agent-based model that we have extended in order to consider non-systematic but conditional enforcement. Three central issues have been emphasized in the joint effect of the stringency and enforcement of environmental policies on eco-innovation: (a) the wider the gaps between strict environmental regulation and strict enforcement, the lower the credibility of the regulation but the higher the possibility of preserving diversity and giving enough time to “mavericks” (firms that take the risk early of developing a cleaner but immature substitute) to expand; (b) very high levels of stringency may prevent the technology from being developed and used at all if the regulation is applied to the letter, because it may alter the competitive process that is vital to preserving diversity and to developing safer substitutes; (c) in some very stringent policy cases, an inverted-U relationship between the credibility of the regulator’s threat such as perceived by firms on the one hand and the stringency of environmental policy on the other hand is illustrated.

[23] “*First, in diagnosing a situation and defining it as a particular kind of policy problem in the first place; second, in interpreting experience with a policy and establishing the context within which minor modifications of the initial program are proposed and debated; and, third, in influencing the broader evaluation of whether the program is basically on track, needs to be changed drastically, or should be killed*” (Nelson and Winter, 1982, p.378).

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Appendix

Time	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
T_{sunset}	155	140	125	110	95	80	65	50	35	20
$\Delta T_{revision}$	22	20	18	16	14	12	10	8	6	4

Table A1- Timing index

Stringency	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
X*	9.36	8.73	8.09	7.45	6.82	6.18	5.55	4.91	4.27	3.64
Eff*	17	16.3	15.6	14.9	14.2	13.5	12.8	12.1	11.4	10.7
α_{watch}	0.05	0.15	0.25	0.35	0.45	0.55	0.65	0.75	0.85	0.95

Table A2- Stringency index

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