# Mind the gap: investigating the impact of implementation gaps on cleaner technology transition

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**Highlights:**

- Policy implementation gaps impact transition to safer chemical substances.
- Low stringency or lax enforcement fails in transition to cleaner technologies.
- Full enforcement of severe policy does not provide the best chance of transition.
- Lenient enforcement of severe policy avoids exit of critical players for transition.

**Abstract:**

Environmental regulation is an important part of many policy mixes for sustainability transitions. However, due to factors including lobbying actions, uncertainty about technological possibilities and costs, there often exists an implementation gap between the regulation and its enforcement. The paper presents an agent-based model to investigate the effect of such implementation gaps on the transition to sustainability for the REACH regulation on dangerous chemical substances. By affecting both the way that heterogeneous actors perceive the regulatory threat and their innovation strategy, implementation gaps may jeopardize the transition to safer substitutes. We show that the combination of the most severe regulation with the strictest enforcement and the shortest timing does not necessarily lead to the highest frequency of bans on dangerous substances, because it may place too much pressure on pioneering firms developing safer substitutes. Opting for a severe regulation should be combined with concessions on enforcement in order to preserve competition and to give 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 relax 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 classification codes:** O33, Q55, D83, Q58, C63

## 1. Introduction

Redirecting and fostering technological change towards cleaner and safer technologies is a key aspect of sustainability transitions. Policies and their combinations play a central role in such a transformation of sociotechnical systems (Markard et al., 2012; Falcone et al., 2019). In this perspective, policy mixes are essential for properly responding to the challenges raised by sustainability transitions (del Rio, 2010; Lehmann, 2012; Veugelers, 2012). Policy mixes refer to the combination of different instruments but also include the processes by which such instruments emerge and interact (Flanagan et al., 2011). Previous theoretical and empirical studies show that they are able to impact the pace and direction of technological change towards cleaner, low-carbon and safer technologies (Rogge and Reichardt, 2016; Kern et al., 2019; Costantini et al., 2017; Reichardt et al., 2016, Hille et al., 2020). By establishing the "rules of the game", policy mixes more or less directly influence the goals and beliefs of actors. Clearly, the sooner and stronger the policy response is, the shorter the slow growth transition phase (Acemoglu et al., 2012). However, 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 to revise or postpone it. Therefore, key questions related to the best policy mix for radically new clean technology are raised: how are stringent policy instruments affected by lenient policy implementation? Do all firms benefit equally or do some suffer more from the impacts of the policy mix? And, given the strong technology and market uncertainty in radical clean technology, how can green entrepreneurs survive when policy goals and the means by which they are implemented are in conflict in a policy mix? This paper proposes an agent-based modeling methodology to provide a preliminary and necessarily incomplete answer to these questions, shedding light on the combined effects of different stringency levels of performance standards (in terms of techno-economic targets, timing and R&D watch) 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.

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 remains unaffected by the postponement of the product ban and that enforcement is mechanically applied as soon as environmental objectives are achieved.[1] In this

[1] 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

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

Recent contributions extend the policy mix concept in order to better apprehend the key policy mix dimensions that impact innovation (Edmondson et al., 2019; Rogge and Reichardt, 2016). Using the analytical framework proposed by Rogge & Reichardt (2016) extending the policy mix concept, we highlight the key features of the REACH regulation. However, not every aspect will be incorporated in the model settings we propose in the paper. Our modeling work focuses on a particular policy mechanism, the authorization procedure, and the fact that its granting is conditional on the availability of economically and technically viable alternatives (*i.e.* innovation) but also on its political acceptability (ultimately affecting the enforcement of the policy).

### 2.1 The policy mix of REACH

Rogge and Reichardt (2016) consider the following dimensions. First, the policy mix is based on a *policy strategy* that defines the long-term objectives and the plans for achieving them, at the EU level or at the national level. The Regulation on the Registration, Evaluation, Authorization and Restriction of Chemicals (REACH)[2] that came into force in 2007 is part of a broader European strategy regarding the innovativeness of the EU chemical industry, as identified in the White Paper on a "Strategy for a Future Chemicals Policy" (2001),[3] and other industrial policy needs as expressed in various EU strategic documents (e.g. EU2020 and Innovation Union). REACH aims at improving the protection of human health and the environment through better and earlier identification of the intrinsic properties of chemical substances, while promoting alternative methods for the assessment of hazards of substances. This is achieved through the four processes of REACH, namely the registration, evaluation, authorization and restriction of

in demand, number of competitors, and number of available technologies. Subsequently, entry barriers are stronger and less entry is possible.

[2] Article 1 of the Regulation states "The purpose of this Regulation is to ensure a high level of protection of human health and the environment, including the promotion of alternative methods for assessment of hazards of substances, as well as the free movement of substances on the internal market while enhancing competitiveness and innovation". In addition, "Special account should be taken of the potential impact of this Regulation on small- and medium-sized enterprises (SMEs) and the need to avoid any discrimination against them."

[3] https://ec.europa.eu/europeaid/sites/devco/files/communication-white-paper-governance-com2001428-20010725_en.pdf

chemicals. REACH also aims to enhance innovation and the competitiveness of the EU chemicals industry. REACH is described as a pragmatic regulation that is both ambitious and realistic in its goals in order to represent a real incentive to undertake innovation (Fuchs, 2011).

Second, the policy mix specifies the *policy instruments* that are needed to achieve the policy strategy. Here the type of instruments (command and control, economic, voluntary, information) and their design features (e.g. stringency, predictability, flexibility or timing) are important considerations for innovation (Kemp and Pontoglio, 2011). Additionally, the choice of *the instrument mix* is far from being neutral and this is the third aspect characterizing a policy mix, according to Rogge and Reichardt (2016). This latter aspect points to the existence of a hierarchy among instruments (core *versus* complementary instruments) but also to the potential interactions between them (IEA, 2011; Flanagan et al., 2011[4]).

The authorization procedure is a specific policy mechanism within REACH used to promote substitution and radical innovation. It 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 *and* only if firms prove that they carry out serious research for alternatives. The authorization procedure is thus one mechanism among a batch of other actions[5] used to achieve long-term targets encouraging a paradigm shift for the production and marketing of chemicals. As regards the substitution and development of new safer chemical substances, such a procedure is central to the regulation as a whole and involves the use of performance standards and the prohibition of harmful substances such that it can be viewed as a mix of command and control instruments that primarily serve a demand-pull purpose (*i.e.* directly affecting technology adoption).[6] As for the design features, the stringency of the REACH regulation is clearly manifest since the consequences of an incorrect application are serious and immediate: they result in exclusion from the market ("No data, no market") (Arfaoui et al., 2014). The level of stringency of the authorization procedure itself will mainly rest on the existence (or not) of economically and technically viable alternatives and on the proof of an R&D watch for alternatives. The flexibility of REACH is also acknowledged since it uses open-ended standards, revisable guidelines, and other forms of "soft law" (Fuchs, 2011). Additionally, by promoting a mode of governance based on the idea of "self-responsibility", REACH involves giving more responsibilities to companies and more flexibility on how to achieve the goals (Fuchs, 2011). The flexibility of the authorization procedure is based on the amount of time afforded to a firm to achieve the performance standards.[7] Regarding the potential interactions between instruments, the most recent assessment report (EC Com 2018)

[4] Flanagan et al. (2011) differentiate between four possible types of interactions: between 'different' instruments targeting the same actor/group; between 'different' instruments targeting different actors/groups involved in the same process; between 'different' instruments targeting different processes in a broader system; between 'the same' instruments across different dimensions (policy field, governance, geography, time).

[5] Registration of chemical substances, Substance Evaluation, Restriction, Communication in the supply chain, and Communication and support tools.

[6] Information and testing requirements are very high in REACH such that it could be classified as an information instrument. We could also consider that the technology-push purpose is present in REACH, although indirectly.

[7] For each substance included on a candidate list, a deadline will be set after which use of that substance in the EU must stop (known as the 'sunset date'), unless authorized.

states that "in principle, the different actions under REACH link together well, and they provide for a good flow of information between each other" (p.96).

Taken together, these three elements (policy strategy, policy instruments and instrument mix) give a snapshot of the policy mix, but it may also be relevant to understand *the policy processes* by which those elements have ultimately been selected and will be reinforced over time, either accelerated or on the contrary slowed down and even abandoned. As argued by Rogge and Reichardt (2016), both the policymaking process (policy adaptation and policy learning) and the policy implementation ("*the arrangements by authorities and other actors for putting policy instruments into action*" (Nilsson et al., 2012, p. 397)) deserve attention for innovation. In the case of REACH, we know that the authorization process for suspect substances has been accompanied by intense lobbying by the stakeholders involved, in addition to the costs incurred due to the process itself (CSES, 2012, p.75). This lobbying action is classical in environmental policy because the policy's expected impacts on competitiveness and innovation are not so clear.

### 2.2 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 come 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 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).

In the case of REACH, the two assessment reports have shown 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 a delayed or postponed schedule when the policy is designed or revised.

### 2.3 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 perspective, 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).

### 2.4 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.[8] In this perspective, 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

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

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 sanctions 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).[9] 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). 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.

### 2.5 Perceived credibility of regulation

When assessing the overall policy mix with different criteria (consistency, coherence, credibility or comprehensiveness), Rogge and Reichardt (2016) argue that "the credibility of the policy mix may play an important role in the achievement of policy objectives and thus in determining the effectiveness of the mix" (p.1627).[10] Indeed, it seems clear that the policy mix will be all the more credible in achieving technology substitution when the policy commitments to future standards are stable and strong, the instrument mix remains consistent in the years ahead to achieve the final long-term strategy, and the coordination between policies from different domains (e.g. environmental, innovation, industrial policy) is ensured.

This is all the more true in that the environmental policy has to deal with many competing interests (from different stakeholders) trying to capture regulation, or that a phase of "collective learning" (Hatchuel, 2008) and changes in cognitive frames (Grin and van de Graaf, 1996) has been initiated because of environmental/health controversies. The final result is the creation of

[9] 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.

[10] The authors finally consider that institutional differences such as those embedded in national innovation systems could also play a role in innovation and ultimately influence the elements of the policy mix.

implementation gaps that, in turn, influence the way firms in the regulated industry perceive the stringency of the policy, *i.e.* its perceived credibility.

As pointed out by Johnstone et al. (2007), there is very wide variation in the perceived stringency of the environmental policy regime; in many of the analyses undertaken, perceived policy stringency turns out to be the most important determinant of private environmental performance and innovation. Based on a wide-ranging empirical study conducted in seven OECD countries, these 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 a 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).

## 2.6 Green entrepreneurs as crucial change agents

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 of 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). Amongst them, the motives of firms called "ethical mavericks" and "visionary champions" (Walley and Taylor, 2002) or "aggressive high growth ventures" (Neumeyer and Santos, 2018) are sustainability oriented and opportunity driven. 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. Theses heterogeneous motives and attitudes are taken into account in the model described below.

## 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 losses 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 insights 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. We amend the model in two ways. First, we use a threshold value depicting the lower limit on the number of suppliers that is politically acceptable. This threshold is a simple way to account for the role played by policy implementation in the policy mix, often characterized by resistance to change due to many risks of competition distortion. Second, we examine the effects of implementation gaps on innovation dynamics in order to show how a command and control approach (the authorization procedure) may not reach its full potential to achieve a successful clean technology transition. 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 between 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

As mentioned in Section 2.6, not every firm perceives new safer alternative substitutes as a strategic opportunity. For the sake of consistency, we propose to qualify as *mavericks* those suppliers that take the risk early of developing a cleaner but immature substitute. At the other extreme, the opportunist and risk-adverse suppliers characterized by a wait-and-see attitude are called *wait-and-see firms*. 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.[11]

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.[12]

### 3.4 Innovation, production costs and pricing strategy

In 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

[11] 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.

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

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.

### 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.[13] In the very first period of the simulation run, each client selects a product through the four-step process depicted in Table 2. 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. The supply chain of chemicals is usually characterized by asymmetric information and knowledge between suppliers and clients (European Commission, 2018a, 2018b). Information flows about product features from manufacturers down the supply chain to downstream users are generally incomplete and downstream users have mostly limited capabilities to process such technical information.[14] As a result, the purchasing process of clients depicted in Tables 2 and 3 is subject to imperfect information and bounded rationality, in the sense that clients are assumed not to be able to perfectly know all the characteristics of all the competing products and they are assumed not to be able to make a perfect assessment of these characteristics. Their purchase decisions rely on satisfying rules based on their own imperfect perception and evaluation of product features, leading to possible sub-optimal choices.[15]

| | |
|---|---|
| Step 1 | The client randomly chooses one product characteristic with probabilities proportional to the client-specific preferences in terms of technical quality of products, 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), negatively dependent on its price and positively dependent on 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 |

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

[14] Improving information and knowledge exchange within the supply chain is a central theme of chemicals regulation. Safety Data Sheets, and now Extended Safety Data Sheets contribute to filling the information gap (European Commission, 2018a, 2018b).

[15] We assume that there is no overproduction or underproduction. Suppliers produce on demand and there is no production limitation to cover demand. However, according to the purchase process depicted in Table 2, some clients may end up without any product because no product on the market meets their requirements.

| | |
|---|---|
| | during the period. |

Table 2 – Decision process for product choice

| | |
|---|---|
| Step 1 | The client randomly chooses one product characteristic with probabilities proportional to the client-specific preferences in terms of technical quality of products, toxicity, and environmental risk of bioaccumulation. |
| Step 2 | The client assigns a score to the product marketed by its current supplier. This score is negatively dependent on the price and positively dependent on the performance feature selected in Step 1. The client compares this score with the best industry score 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 score of its current supplier 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

### 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.

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. 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. 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, called *MinSuppliers* 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.[16] 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.[17] Finally, in the context of multiple complex negotiations involving bounded rational agents, "preserving a minimum number of competitors" is a simple workable rule from which stakeholders are able to define a compromise as to the level of this threshold. 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 are a set of environmental policy tools and firm-specific perception. They 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. 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. In particular, 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 may impact innovation.

| **Description** | **Computation** |
|---|---|

[16] 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 modeling exercise and it would dramatically complicate the model and blur its results.

[17] 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.

| | |
|---|---|
| *Target*: extent of the threat with respect to techno-economic performance targets.<br>The closer the average performances of T2 to the performance target thresholds, the higher the extent of the threat.[18] | $Target_t = min\left(\frac{AvX_{t-1}}{X^*};\frac{AvEff_{t-1}}{Eff^*}\right)$<br>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.<br>The closer the sunset (or revision) date, the higher the extent of the threat.[19] | if $t \leq T_{sunset}$:<br>$Timing_t = \frac{t}{T_{sunset}}$<br>if $t > T_{sunset}$:<br>$Timing_t = 1 - \frac{T_{revision} - t}{\Delta T_{revision}}$<br>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).<br>The greater the number of postponements of the regulation, the lower the extent of the threat.[20] | $Enforce_t = 1 - \frac{Post_{t-1}}{maxPost}$<br>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.<br>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 by a factor (1 – *Threat*). Second, the two-step decision procedure used 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

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

[19] *Timing* ∈ [0; 1].

[20] *Enforce* ∈ [0; 1].

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). The initial choice of parameters was made by considering three sets of parameters as suggested by Filatova et al. (2013): empirically based parameters, technical parameters, and empirically uncertain parameters. 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)[21] in order to account for the differences between bisphenol-based materials and bio-based substitution materials, as empirically observed. A sensitivity analysis to empirically uncertain parameters based on a Monte Carlo procedure 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 $a_{watch}$, 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.[22]

### 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 the values of the empirically uncertain parameters set randomly in order to generate a large number of possible outcomes covering a diversified subset of the parameter space. Among these parameters, we focus on those depicting policy features, namely *Time*, *Stringency* and *MinSuppliers*. 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

[21] These reports of the French National Institute for Industrial Environment and Risks (INERIS) contain a set of baseline information on bisphenols about basic technical and regulatory data, toxicological data, the uses of bisphenols, the presence of bisphenols in the environment and alternatives to bisphenols and bisphenol-based materials.

[22] 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.

(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 prohibition occurs (Figure 2) and the inverse Herfindahl–Hirschman index of concentration[23] (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.[24]

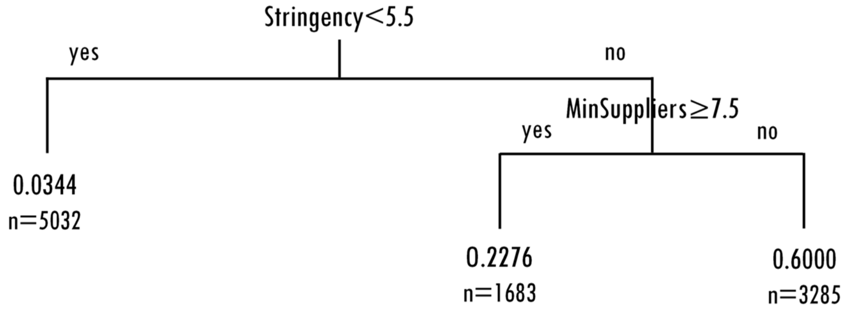


Figure 1 – Regression tree of T1 prohibition frequency

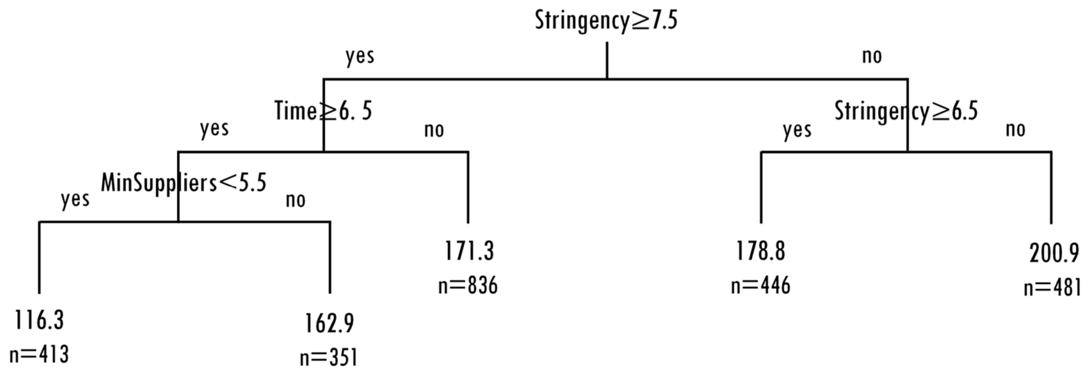


Figure 2 – Regression tree of prohibition time period

[23] 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.

[24] For instance in Figure 1, on the left branch of the tree, we have all observations for which *Stringency*<5.5. On the right branch, we have all observations for which *Stringency*≥5.5. There are *n*=1,683 observations out of 10,000 for which *Stringency*≥5.5 and *MinSuppliers*≥7.5, and in this case the frequency of T1 prohibition is 22.76%.

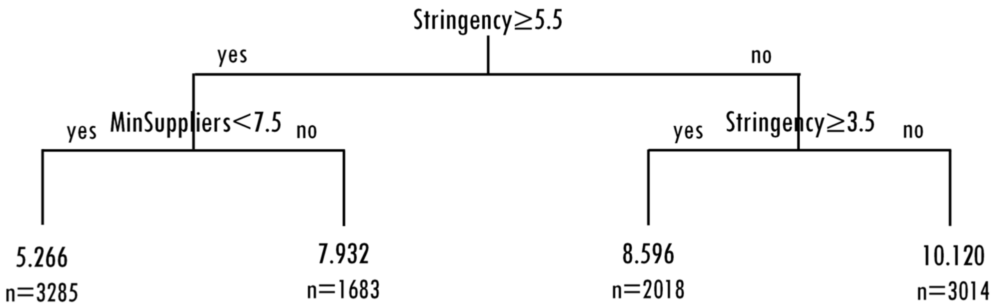


Figure 3 – Regression tree of inverse Herfindahl–Hirschman index of concentration

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 Figures 1 and 2, one can note that, if the policy is not sufficiently severe, the chances of T1 prohibition are very tenuous (6.45% if *Stringency*<5.5), and in the few cases it occurs, it does so late (*t*=200.9 if *Stringency*<6.5).

The question of policy enforcement, depicted by *MinSuppliers,* 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 two and a half times as much (22.76% vs. 60%). Thus, the highest frequency of T1 prohibition (60%) is observed when the stringency index is sufficiently high and the threshold of suppliers is sufficiently low (*Stringency*≥5.5 and *MinSuppliers*<7.5). 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*≥7.5 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 second 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.

These results suggest that the hierarchy of instrument design features may be as important to consider for innovation as the hierarchy of instruments in the instrument mix (core vs complementary instruments). 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 acceptable number of suppliers 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).[25] Table 5 recaps the examined cases.

| | | |
|---|---|---|
| Stringency | From loose to severe | *Stringency=1;2;…;9;10* |
| 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.[26] 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 5 is needed to guarantee a high likelihood of transition. However, as already mentioned, the combination of the most severe regulation (*Stringency*=10) with the strictest enforcement and the shortest timing (Strict – Short) 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 8, reaches a maximum at almost 92% before dropping as stringency continues to rise from 8 to 10, finally standing at 81%. 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.

[25] 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 the value for *Stringency* set randomly. 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).

[26] A complementary graph is appended (Figure A1 in appendix) displaying the optimum level of stringency according to varying degrees of timing and enforcement thresholds.

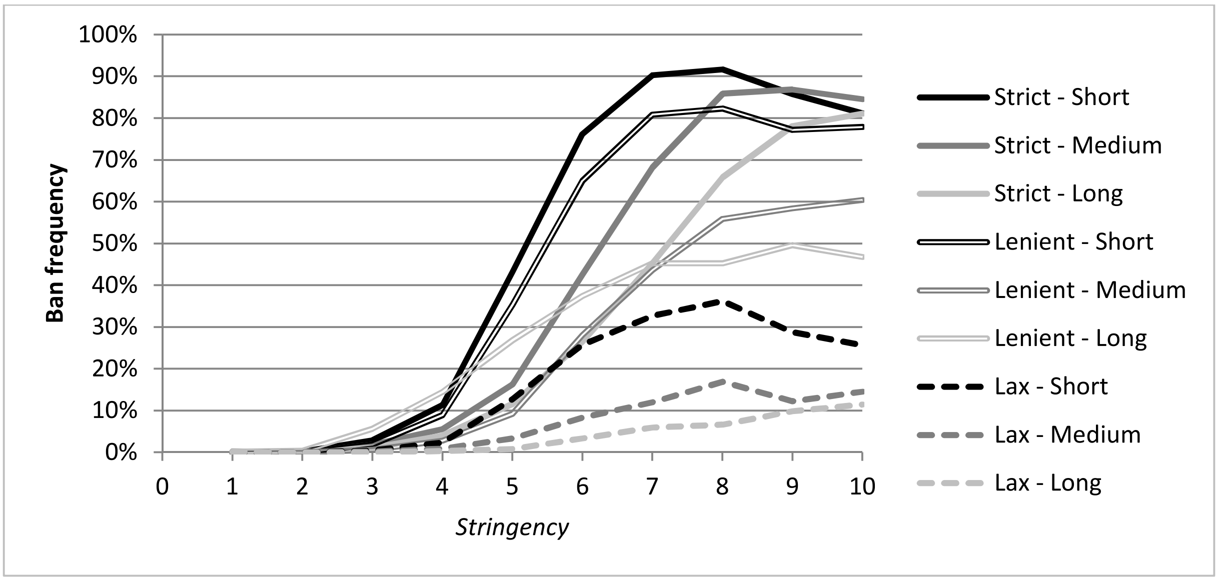


Figure 4 – Frequency of T1 bans according to varying degrees of stringency, timing and enforcement thresholds

The explanation rests on the pressure mechanism that makes the authorization to produce, market and use harmful substances conditional upon 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 of the market too early. The regulatory pressure forces green pioneers to prematurely stop 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[27]

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 (*Stringency*=10) and timing is short, the likelihoods of T1 prohibition (ban frequency) obtained with strict or lenient enforcement are very close (respectively 81% *vs* almost 78%). 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 3.12 *vs* 5.33), and the number of surviving firms is significantly higher (respectively 3.58 *vs* 6.15).[28] Also, in terms of likelihood of transition, the system under lenient enforcement performs equally, even slightly better, as indicated by the T2 market share indicator, which amounts to 83.24% against 81.76% 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 (2.40) than lenient enforcement (6.98). 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 significant increase in the ban frequency (84.6% rather than 81.1%) and T2 market share (85.2% rather than 81.8%) 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.

| Values at t=250 | Enforcement threshold | | |
|---|---|---|---|
| | Strict | Lenient | Lax |
| T1 ban frequency | 81.1% *(*)* | 77.9% | 25.6% *(***)* |
| T2 market share | 81.8% *(n.s.)* | 83.2% | 36.5% *(***)* |
| Inverse Herfindahl – Hirschman index | 3.12 *(***)* | 5.33 | 8.34 *(***)* |
| Average number of | 3.58 *(***)* | 6.15 | 9.88 *(***)* |

27 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, 4 and 10. Significant differences occur for the other cases (i.e. stringency levels from 5 to 8 are significant at 1% and level 9 at 5%).

28 We can note that an increase in market concentration goes together with larger mark-up rate for both T1 and T2.

| | | | |
|---|---|---|---|
| competitors | | | |
| Average number of competitors when no T1 ban | 2.40 *(***)* | 6.98 | 11.16 *(***)* |
| Average mark-up T1 | 0.81 (***) | 0.61 | 0.60 (*n.s.*) |
| Average mark-up T2 | 0.84 (***) | 0.75 | 0.67 (***) |

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)[29]

| Values at t=250 | Enforcement threshold | | |
|---|---|---|---|
| | Strict | Lenient | Lax |
| T1 ban frequency | 84.6% *(***)* | 60.5% | 14.5% *(***)* |
| T2 market share | 85.2% *(***)* | 66.3% | 25.7% *(***)* |
| Inverse Herfindahl – Hirschman index | 3.19 *(***)* | 5.48 | 9.18 *(***)* |
| Average number of competitors | 3.69 *(***)* | 6.41 | 10.84 *(***)* |
| Average mark-up T1 | 0.86 (***) | 0.64 | 0.61 (***) |
| Average mark-up T2 | 0.86 (***) | 0.73 | 0.61 (***) |

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)[30]

In terms of policy implications, opting for a very stringent regulation in terms of severe performance targets and short timing should go together with concessions on enforcement and tolerance of 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 relax 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. In that case, the likelihood of T1 being prohibited is rather low (14.5%), generating, on average, low diffusion of T2 (25.7%) in spite of low market concentration (9.18). 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, whereby 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* 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

[29] 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 and (*) at the 10% level. (n.s.) stands for 'not significant'.

[30] See footnote 19.

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).[31] 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.

Our analysis contributes to the literature on the link between policy mix and innovation 1) by establishing the hierarchy of design features and 2) by explicitly considering the dynamic interplay between design of core policy instrument and implementation. The results reveal a direct link between such policy processes and technological change. The use of an agent-based model is particularly helpful to investigate how firms' choices are affected by such a complex interplay, especially the credibility they give to the policy mix. Indeed, we show that the lack of efficiency resulting from coupling very strict objectives with full enforcement is caused by the fact that the cut-off penalty falls prior to the advent of mature mavericks. 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 R&D watch on substitutes is above a certain level (see Section 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 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

[31] 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.

the number of competitors due to strict enforcement, negotiating parties should compromise in order to reach a less severe agreement, thus leading to sufficient diversity of strategies. However, there are limits to such compromises since the loss of credibility resulting from excessively high 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,[32] 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

[32] 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)

policies and competition policies should further consider maintaining multiple sources of variation and innovation.

As regards the elements of the policy mix developed in the framework proposed by Rogge and Reichardt (2016), we see three main limitations of the modeling work proposed in this paper. First, it has examined one single category of policy instrument (command and control), ignoring the potential role played by interlinkages across different types of environmental policy instruments (market-based, soft and systemic). To address the problems of green innovation, innovation policy instruments (e.g. R&D subsidy, support to venture capital or public procurement) should also be part of the design of an instrument mix, or set of different and complementary instruments (Borrás and Edquist, 2013). Second, the parametrization lacks explicit sectoral characteristics accounting for sectoral specificities in patterns of technology advances and the characteristics of innovative actors (Schumpeterian regimes or sectoral systems of innovation and production). This would allow better characterization of the interactions between actors in the supply chain and a better accounting for feedback from suppliers and final consumers (knowledge spillovers). Third, we assumed a fixed posture during the whole simulation period for the agency responsible for checking the process. However, the policy-learning dimension is part of the policy mix framework. As pointed out by Edmondson et al. (2019, p.3), "a constant realignment of policy with the changing conditions of the socio-technical system is necessary […], requiring reflexive policymaking and learning over time to account for the unpredictable nature of transitions". Thus 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. 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 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. A successful transition towards sustainability might then require carefully and properly designed policy addressing the inherent complex interplay between design of core policy instruments and enforcement. In particular, an overarching aspect to address for such structural changes to arise is to support green marginal pioneers in the early phase of development, when their disrupting technologies still underperform in focal attributes. The regulatory framework should avoid putting excessive pressure on the so-called mavericks and should provide protected and suitable areas for their niche cleaner and safer technologies to develop and ultimately break the lock-in of the incumbent regime.

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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 |
| $a_{watch}$ | 0.05 | 0.15 | 0.25 | 0.35 | 0.45 | 0.55 | 0.65 | 0.75 | 0.85 | 0.95 |

Table A2- Stringency index

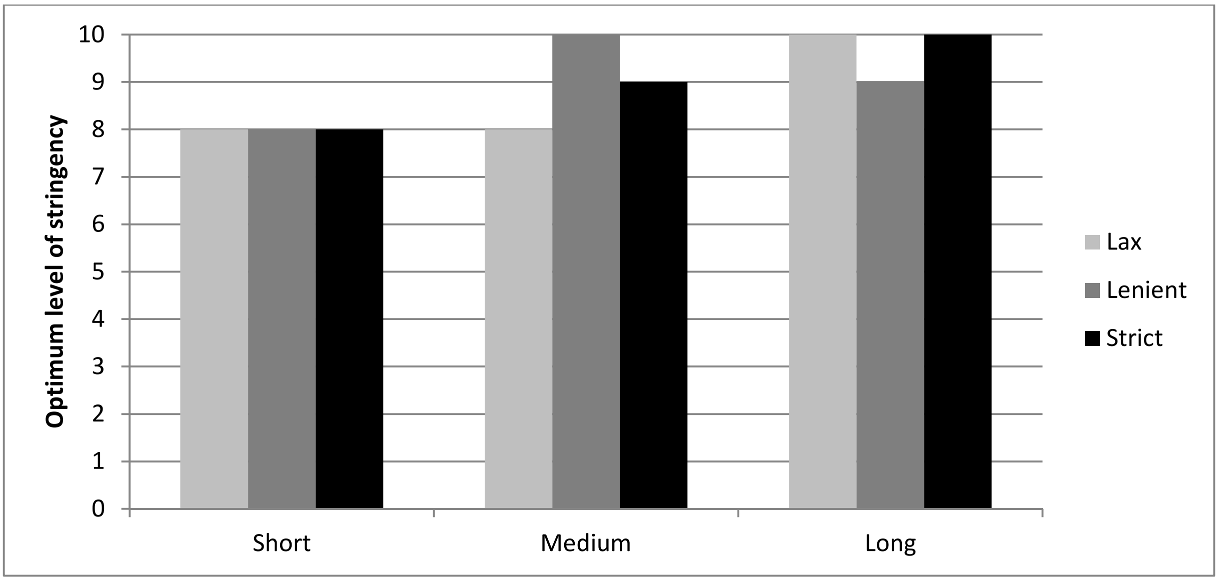


Figure A1- Optimum level of stringency according to varying degrees of timing and enforcement thresholds

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