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Fostering safer innovations through regulatory policies: The case of hazardous products

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Abstract:

We consider the case of a firm selling a product which can cause damage to consumers (e.g. a product containing hazardous chemicals which can cause diseases). The firm has the possibility to make an effort in R&D in order to discover a new substitution product. This R&D could lead to a new but more dangerous product than the historical product (situation of "regrettable substitution"). We compare four policy regimes (two forms of *ex ante* approval, civil liability, and a combination of approval and civil liability) according to their impact on the firm's decisions (R&D, and technological choice) and their consequences on social welfare. We find that the ranking between policy regimes mainly depends on the public regulator's expertise (for approval), the type of the risk which is under consideration and/or the potential impact of R&D on the degree of dangerousness.

JEL Code: D21, D62, L51, K13

Key words: public regulation, innovation, technical choice, (health) hazard

I. Introduction

Exposure to hazardous substances, in the workplace as well as through consumption goods, is a growing social concern. Previous debates have centered around the use of asbestos, GMO, etc. Currently there are at least two ongoing debates about substances which are present in consumption goods: nanoparticles (see Lacour (2009), Laurent (2010), D'Silva (2012), Falkner and Jaspers (2012)), and "endocrine disruptors"[2] (see ANSES (2013)).

These debates are highly controversial, because they are taking place while many uncertainties still hold. A first uncertainty concerns the dangerousness of the suspected substances themselves. For the case of bisphenol A, for instance, studies in toxicology lead to different conclusions from studies in endocrinology (see Dietrich *et al.* (2013), Bergman *et al.* (2013)). Moreover, in some cases, uncertainty may also arise regarding the dangerousness of the potential substitutes for the suspected substances: to ban a dangerous substance can be socially desirable, but it is also important not to replace this substance by a

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[2] Endocrine disruption is the ability to affect the hormonal system. Several chemical substances, especially bisphenol A, are suspected of adversely affecting the hormonal system, causing cancers or fertility problems.

more dangerous one. Such cases of "regrettable substitution" have already occurred in the past. Tuncak (2013) describes the case of a regrettable substitution in chemical flame-retardants: some flame-retardants were replaced by others having a similar chemical structure. However, as summarized by Tuncak (2013): "*A chemical's form and function are closely linked. The form of a molecule determines both its function in a polymer, as well as its function in biochemical pathways, which may lead to adverse effects. Although slight changes to a chemical's structure can make a difference in terms of its physical or biological functionality, there is a significant likelihood that the substitute chemical will not be devoid of intrinsic hazardous properties*." (p 14). He also describes a case of "questionable substitution" (no scientific certainty) in the substitution of phthalates. Nowadays, a similar discussion is focusing on the case of endocrine disruptors, and especially bisphenol A (BPA). As substitutes for BPA in food containers, bisphenols S and F were introduced. However, their degree of dangerousness is not perfectly known: regrettable substitutions cannot be excluded (see Danzl, E. et al (2009), Vinas and Watson (2013), Kinch, C.D. et al (2015), Eladak, S., et al (2015)).

The presence of such a (potential) negative externality of production calls for a public regulation, even in the absence of scientific consensus: invoking the Precautionary Principle, some countries introduced bans on "suspected" products or substances. Sticking to the example of BPA, France banned its use in food containers on 1st January 2015, thereby constraining industrial firms to develop and use substitutes. In the paper at hand, we address the issue of providing incentives to develop substitutes, explicitly taking into account the possibility of "regrettable substitutions". We compare four public policy instruments (two types of technical approvals, civil liability, and a combination of approval and civil liability) in terms of incentives to invest in R&D and to use a safer product (as well as incentives to not to use a more dangerous product).

Such an analysis is relatively new in economics. Until the late 2000s, public risk regulation and public incentives for innovation were treated independently. As a consequence, two important issues were neglected: on the one hand, no study considered the possibility of innovating in order to reduce a (technological) risk of accident and, on the other hand, no study took into account the risks (of accidents) associated with innovative processes.

More precisely, from the 1970s the movement of *law and economics* analyzed how the civil liability system can provide incentives to reduce the risks of (technological) accidents. Due to the threat of financial penalties (called *damages*) for harm caused to others, civil liability can provide decision makers with incentives to reduce the level of risk their activity incurred to others, in many different economic contexts (see Shavell (1980, 1986), Boyd&Ingberman (1994), Pitchford (1995), Dionne&Spaeter (2003), Dari-Mattiacci&DeGeest (2005), etc.). But these studies do not take into account the possibility of innovating in order to improve the efficiency and/or the safeness of their production process.

Providing incentives to innovate in order to mitigate a negative externality of production is an issue which has been addressed by environmental economics. The negative externality is not a risk of damage, but pollution associated with a production process.

Following the pioneering work of Zerbe and Magat (Zerbe (1970), Magat (1978, 1979)), environmental economists analyze how different environmental policy tools provide incentives to abate pollution, and to develop, use and diffuse more efficient abatement technologies (see Downing & White (1986), Milliman& Prince (1989) among the classics). The most recent studies take also into account the specificities of the R&D market, especially the presence of spillovers (e.g. Fischer et al. (2003)) and the interactions between the research sector and the industry which is the source of the pollution (e.g. Parry (1995), David & Sinclair-Desgagné (2010), David et al. (2011)). From the late 2000s, this literature extends to other policy tools, like civil liability (Endres *et al.* (2006, 2008), Endres&Friehe (2011)). But these studies remain focused on the problem of effluent regulation, which is not always relevant to the questions of *risk* regulation.

To our knowledge, the first studies to investigate the link between public regulations and R&D in industries displaying *a risk of* damage to Society are those of Immordino *et al.* (2011) and Jacob (2013, 2014). Jacob (2013, 2014) compares the incentivizing power of different forms of civil liability in undertaking R&D that improves the efficiency of industrial safety systems. So only one policy tool is analyzed, and R&D is always welfare improving: he does not consider the possibility of regrettable substitution.

The first study to develop a comparative analysis of different policy tools is that of Immordino *et al.* (2011). They compare *laissez-faire*, *ex ante* authorization (technical approval), and *ex post* penalties in terms of incentives to invest in R&D to develop a new product, which could be either beneficial or detrimental to Society. Therefore, as in the paper at hand, they take into account the possibility of regrettable substitution. However, our two contributions differ each other in some of their important assumptions.

First, we consider that a higher R&D effort increases the likelihood of finding a safer substitute while Immordino *et al.* (2011) consider an exogenous probability of a substitute being beneficial or harmful.

Second, *ex ante* authorization processes are quite different between our contributions: Immordino *et al.* (2011) consider a given, invariant and exogenous probability of the public authority discovering the degree of dangerousness of the product. In our study, we instead consider that the probability of the public authority granting authorization depends on two elements: the intrinsic degree of expertise of the regulator (and we test for different degrees of expertise), and the level of effort in R&D made by the firm. We introduce the possibility of the regulator making errors, and especially of granting authorizations to dangerous products (while such a possibility is excluded in the "strict authorization" policy of Immordino *et al.* (2011)).

Finally, we study the incentives provided by a ban on the basic product, and by civil liability: these two policies are excluded by Immordino *et al.* (2011). Indeed, the regulator can enforce a ban on a suspected product, as France did with BPA in 2015. We take this possibility into account, while Immordino *et al.* (2011) consider that the firm always has the possibility of "statu quo" action (only the new product can be banned by the regulator). The system of penalties introduced by Immordino *et al.* (2011) can be seen as a civil liability system, but they suppose that fines are enforced only when the regulator is able to prove that the product is harmful (and this probability is the same as for the authorization policy). Instead, we assume that the firm has to pay for damages as soon as damage occurs, the probability of which depends on the real degree of dangerousness of the product (and not on the regulator's performance); these assumptions are more realistic and allow the introduction of additional differences between *ex ante* and *ex post* policies.

We can note that other (and older) studies compare different policy instruments that aim to regulate risky activities. Shavell (1984) analyzed the role of four determinants of the choice between *ex ante* authorization and *ex post* penalties in the regulation of risky activities. Following this seminal work, Shavell (1984b) and Hiriart *et al.* (2004) analyze the optimal articulation between *ex ante* and *ex post* regulations. However, these contributions set aside the issue of R&D and its possible detrimental effects: they focus on the way to encourage prevention for a given degree of technical progress. Finally, we find no academic economic study specifically dedicated the issue of providing incentives to search for substitutes for (chemical) substances.

We find that the ranking between the different decentralized policies (and especially ex ante vs ex post) is not frozen: it depends on the skills of the regulator, on the firm's ability to get value from the public label provided by approval processes, and on the characteristics of the risk of accident.

For instance, when enforcing approval processes, we show that an extremely competent regulator is not necessarily desirable because the firm cannot alter its "opinion" (i.e. the probability of getting approval) via a higher level of R&D: incentives to provide R&D efforts are lessened. In particular, when the process of approval is *not* associated with a ban on the old product, we show that the presence of an extremely competent regulator on which the consumers didn't trust does not allow the approval process to dominate civil liability: only a sufficiently high ability to get additional revenues by obtaining the approval (i.e. to get money thanks to "public labeling") allows approval to dominate civil liability in such a case.

The ranking between the different policies also depends on the characteristics of the risk of accident: the higher the probability of accident associated with the introduction of a dangerous substitute, the more desirable civil liability relatively to all types of approval processes. Conversely, the higher the potential damage, the more desirable a process of approval associated with a ban on the old product.

These results are quite different from those of Immordino *et al.* (2011), who highlighted a principle of increasing stringency of the public regulation as the probability of facing a dangerous product increases. Here, because of the possibility of an imperfect degree of expertise of the regulator and because the probabilities of finding a safer substitute and getting approval are endogenous (through investment in R&D), there is no such linearity in the ranking between the different decentralized policies.

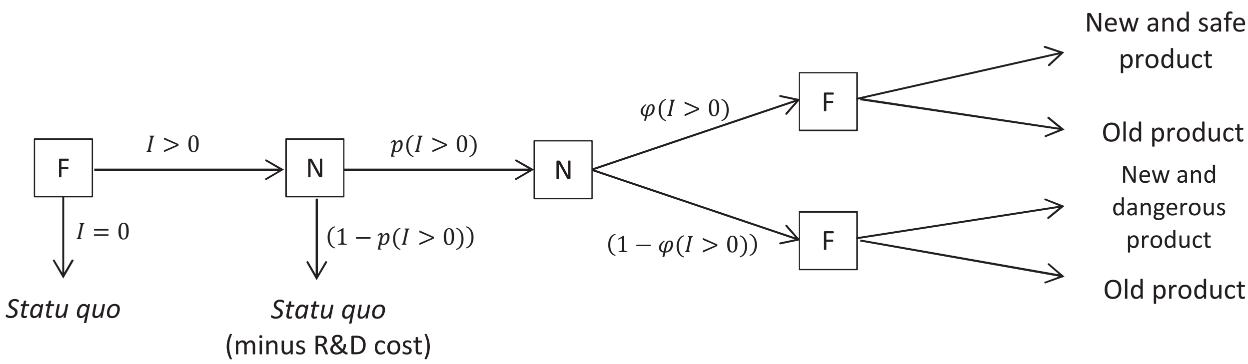
The paper is organized as follows: section II introduces the basic assumptions of the theoretical analysis; section III presents the first-best equilibrium; section IV presents the different decentralized policies, which we compare in section V. Section VI concludes.

II. Setup

Let us consider a risk-neutral firm on a competitive market, selling a product which can be the source of harm to human health. This product is essential and widespread: it cannot be completely overlooked by consumers, so that there is always a demand for this product whatever the risk to consumers' health (e.g. plastics). For the moment, consider this product to have no alternative. Nevertheless, the firm has the possibility of investing in R&D in the hope of finding an alternative product which is less dangerous (and that meets the same consumers' needs). Let us denote the effort in R&D by I, and implementing I has a cost $k.I$, $k > 0$.

The different decisions and state of Nature can be described by the following decision tree.

Figure 1. Decision tree (setup description)



If the firm (F) does not invest in R&D ($I = 0$), Society remains in the *statu quo* situation: only the old product is available. This product can inflict a damage H on the rest of Society (damage to human health), with a probability q.

If instead the firm invests a strictly positive amount $I > 0$ in R&D, then Nature (N) decides whether R&D succeeds or not. With a probability $p(I > 0)$, R&D succeeds and a new product is discovered, with $p' > 0, p'' < 0, p(I \to \infty) < 1, p(I = 0) = 0$. With the complementary probability, Nature decides that R&D fails, so that no new product is discovered and Society remains in the *statu quo* situation (while the firm loses the cost $k.I$ of R&D).

As is the case within some industries (e.g. chemicals), a new product is not always safer than an old one (see Tuncak (2013)). As a consequence, in case of successful R&D, there is a probability $\varphi(I > 0)$ that Nature chooses the new product to be safer than the old one (with $\varphi' > 0, \varphi'' < 0, \varphi(I \to \infty) < 1, \varphi(I = 0) = 0$). In this state of Nature, the new product is associated with a low probability of damage q_0, with $0 < q_0 < q < 1$. In the other state, occurring with a probability $(1 - \varphi(I > 0))$, Nature chooses the new product to be more dangerous than the old one: it is associated with a high probability of damage q_1, with $0 < q < q_1 < 1$. This latter state is less likely to occur when the amount of investment in R&D is high: $\varphi' > 0, \varphi'' < 0, \varphi(I \to \infty) < 1, \varphi(I = 0) = 0$. Whenever R&D succeeds, the firm faces a choice between selling the old product or the new one.

Let us also suppose that selling the old product allows the firm to earn a net operating revenue W and that successful R&D always allows the firm to benefit from a higher operating revenue than under the *statu quo* situation. This may be the consequence of efficiency gains in the production process due to innovation, and/or the consequence of a higher appeal of the new product to consumers. Supposing that R&D improves the functional quality of products (irrespective of their dangerousness), we assume that consumers have a preference for new products (i.e. higher willingness to pay than for old ones); and they are able to detect novelty. Moreover, consumers have a preference for safety: *ceteris paribus* they have a higher willingness to pay for safe products (than for unsafe ones). But without *credible* information (see below), they are unable to distinguish a safe product from an unsafe one.

As a consequence, when R&D succeeds in obtaining a new and safe product, the firm earns a net operating revenue W_0, with $W_0 > W$, provided that *credible* information is disclosed to consumers. Otherwise, a new product permits the firm to earn a net operating revenue of W_1, with $W_0 > W_1 > W$. In other words, when R&D succeeds the firm can extract the consumers' willingness to pay for novelty ($W_0 > W$, $W_1 > W$) and, when it is possible to disclose credible information on safety, the firm can extract an (additional) consumers' willingness to pay for safety ($W_0 > W_1 > W$). Information (on safety) is *credible* to consumers when it can be *"labeled"* by a public authority.[3]

From a social point of view, we suppose that a new but more dangerous product leads to a decrease in social welfare: the increase in the firm's operating revenue ($W_1 > W$) does not offset the increase in the risk of damage ($q_1.H > q.H$) that is borne by Society: $W_1 - q_1.H < W - q.H$. Hence private benefits conflict with social welfare in this situation. Last, we consider that the magnitude of harm always exceeds the firm's revenue ($H > W_0$).

We will now identify the first-best situation, i.e. the (social) benchmark situation to which public regulation should help us get closer.

III. First-best situation

As is usually done in the literature,[4] the first-best situation can be derived when considering a hypothetical situation in which the public regulator has all information and directly controls all the firm's actions, in such a way as to maximize a social welfare that takes into account all social benefits and costs from activity (situation of an omniscient, omnipotent and benevolent dictator).

[3]On the disclosure of information on safeness, it is reasonable to assume that a public authority is more credible (to consumers) than a private firm. Such a relative credibility is sufficient for our purpose.

[4] See Endres *et al.* (2006, 2008), Jacob (2014), or Shavell (1986) for instance.

Figure 2. Decision tree (with social payoffs)

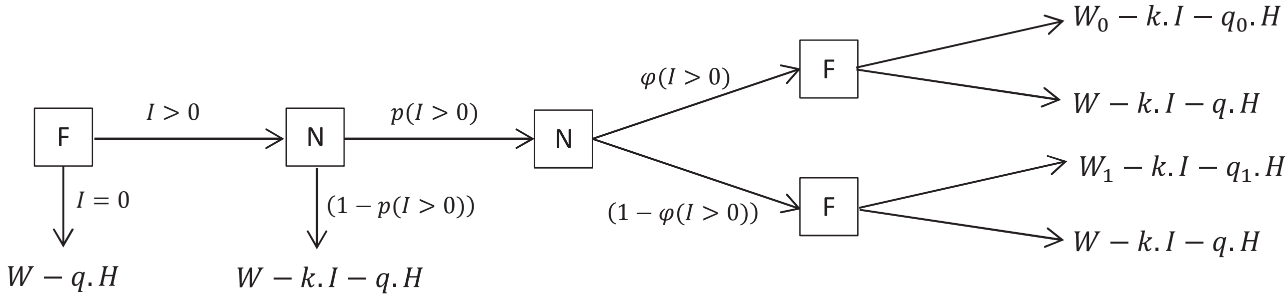


Figure 2 above describes the alternatives the firm faces in a social perspective, depending on different states of Nature. A social perspective means considering social payoffs for the different alternatives (taking into account all social benefits and costs), and considering socially optimal decisions.

In case of successful and safe R&D, it is socially desirable for the new product to be commercialized (upper branch). The social welfare is equal to: $W_0 - k.I - q_0.H$. Indeed, in this first-best situation, the public regulator is aware on the state of Nature and can disclose credible information to consumers on the safeness of the new product. This credible information provides a high utility to consumers (W_0 can be extracted).
Knowing that a new but more dangerous product is not socially desirable, the *statu quo* situation (keeping the old technology) is adopted when R&D is unsuccessful and when it leads to a dangerous new product (bottom branch). As a consequence, in the "but for successful and safe R&D" state, the social welfare is: $W - k.I - q.H$. When no R&D is undertaken, *statu quo* also prevails so that the social payoff is: $W - q.H$.

Following the above reasoning, we can write the first-best expected welfare that a public regulator (acting as a benevolent dictator) has to maximize as:

$$\max_I W(I) = p(I).\varphi(I).[W_0 - q_0.H] + [1 - p(I).\varphi(I)].[W - q.H] - k.I \qquad (1)$$

The socially optimal amount of R&D, I^{**}, is such that:

$$\frac{\partial W(I)}{\partial I} = 0 \quad \Rightarrow \quad p'(I).\varphi(I) + p(I).\varphi'(I) = \frac{k}{W_0 - W + H(q - q_0)} \qquad (2)$$

The first-best equilibria being provided, we will now analyze the (real) decentralized setup and introduce the different regulatory policies.

IV. Regulatory policies: a presentation

In this section we introduce the different public regulations, and we describe their influence on the firm's behavior and their consequence on social welfare. A comparative evaluation of these policies will be then provided in section V.

A. Authorization / Technical approval

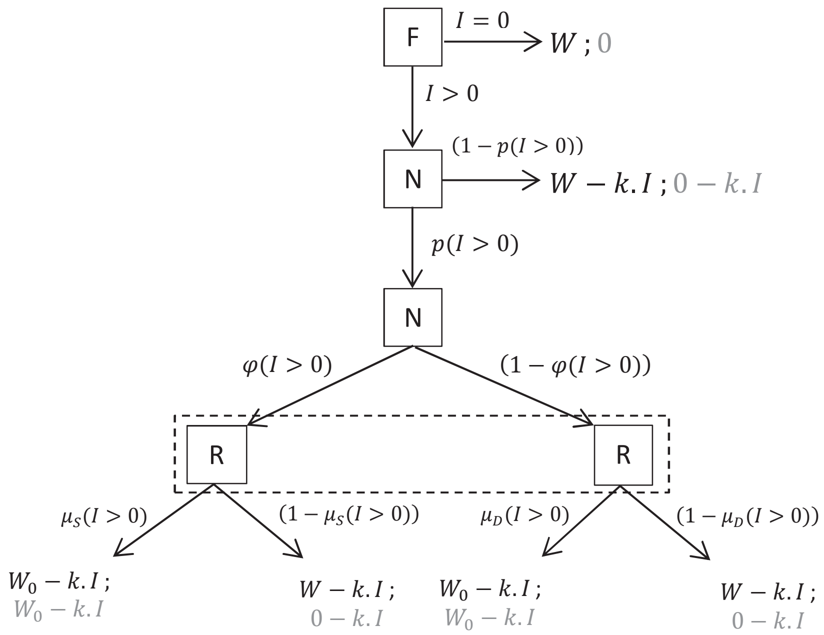
Under such a regulation, the firm has to present the new product before a public regulator to obtain an authorization to get it on the market. By making its own evaluations, the public regulator balances the social benefits and costs that the new product can provide and decides to grant, or not, the authorization to the firm to operate with this product.

Given our assumption that a new product always provides higher net operating benefits (i.e. $W_1 > W$ and $W_0 > W$), the evaluation of the regulator only consists in determining whether the new product is more or less dangerous than the old one.

We distinguish two types of approval systems: *soft* approval, and *hard* approval. Under *soft* approval, in the "but for approval" event the firm can operate with the old product. Under *hard* approval, approval is combined with a prohibition of the old product: if the firm does not obtain the authorization to exploit the new product, it cannot operate with the old one; so its profit falls to zero.

The situation the firm faces can be represented as in the Figure 3 below:

Figure 3. Decision tree, with private payoffs under soft approval; hard approval in grey



The figure above describes all the possible situations and decisions under approval, and the corresponding firm's private payoffs: payoffs under *soft* approval are mentioned in black, payoffs under *hard* approval are mentioned in grey.

As with the social planner's problem, the firm has first to choose whether to invest or not in R&D. If not, it enjoys the old product in case of soft approval; it cannot under hard approval: the new product is banned, its profit falls to zero. In case of investment, R&D can succeed or not. In case of failure, the firm has to use the old product (soft approval) or its profit falls to zero (hard approval). In case of successful R&D and whatever the dangerousness of the new product,[5] the firm presents its innovation before the public regulator (in order to obtain an authorization to operate). It is important to note that the firm knows whether Nature has decided the new product is safer than the old one (left side), or whether Nature has decided the new product is more dangerous than the old one (right side). However, this information is private to the firm: when a product is presented before it, the regulator does not know the dangerousness of the product. So it has to make a technical assessment to determine its dangerousness. If the regulator concludes that the new product is "safe", the firm can enjoy it (whatever the type of approval). If the regulator concludes that the new product is "dangerous", the firm has to use the old one (soft approval) or its profit falls to zero (hard approval).

Who is the regulator we are talking about?

We assume the regulator to be a public and independent agency that grants an authorization (or not) to place new products on the market after an assessment process. In order to simplify the analysis we assume the public regulator not to be a player (in the sense of game theory): no decision is made. Instead we assume that when presenting its product, the firm faces a binary lottery: there is a probability of the new product being authorized and a complementary probability of it not being authorized.

Let us denote $\mu_j(I)$ the probability that the regulator grants approval, with $j = S, D$ denoting the level of dangerousness of the new product (S for "safe", occurring with probability $\varphi(I)$, D for "dangerous", occurring with probability $(1-\varphi(I))$), $0 < \mu_j(I) < 1$. (1-$\mu_j(I)$) is the probability of the new product being prohibited.

We assume the probability $\mu_j(I)$ of the new product being granted to depend on two elements.

First, whatever the real degree of dangerousness of the product, we suppose the higher the effort I in R&D, the higher the probability of the new product being approved (with a decreasing return: $\mu_j{}'(I) > 0$, $\mu_j{}''(I) < 0$, $0 < \mu_j(I) < 1$, $\mu_j(I \to \infty) < 1$).[6]

Second, we assume the regulator to have some degree of expertise, which is represented by the magnitude of the difference $\mu_S(I) - \mu_D(I)$. Indeed, having $\mu_S(I) - \mu_D(I) > 0, \forall I$ means

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[5] Supposing the existence of random on-site controls by a public authority, sufficiently high fines can deter the firm from being deviant (i.e. to not present its innovation before the regulator for approval, and/or to not comply with a non-approval/prohibition of the innovation by the regulator).

[6] Some findings in the literature about R&D in the pharmaceutical industry support our assumption. Di Masi *et al* (2003) find evidence about the costs for more significant new molecules: those being ranked as "priority" by the FDA (and having a higher chance of being granted) are associated with higher R&D budgets. Di Masi *et al* (2016) underline that "*the literature also indicates that firms with larger R&D pipelines and greater R&D experience have a higher probability of success during the costly clinical stages of drug R&D*" (p 29). They especially cite Danzon *et al* (2005) and Pammolli *et al* (2011): the first study finds evidence of a positive relation between the probabilities of success in the different phases of clinical tests (phase III being the approval by the FDA) and the firm's R&D experience. They highlight that larger firms have a comparative advantage in the last stages of the R&D process (these stages being the most regulated). Pammolli *et al* (2011) find that the firm's size is important in the success of R&D and, controlling for the size, firms who are able to exploit the international division of R&D skills (i.e. having R&D centers on both sides of the Atlantic, which can be used as a proxy for R&D effort) are more productive.

a safe product having a higher likelihood to be approved (than a dangerous one), for a given effort in R&D. This reflects some ability by the regulator to (imperfectly) distinguish the type of product, independently of the firm's effort. A first extreme case could be the presence of an *"extremely competent"* regulator, who is able to perfectly discriminate between the two kinds of products, independently of the firm's effort: $\mu_S(I) = 1, \mu_D(I) = 0, \forall I$ (the regulator approves all safe products, and rejects all dangerous ones). The other extreme case is the presence of an *"extremely myopic"* regulator, who is unable to distinguish between the two types of products: $\mu_S(I) = \mu_D(I) = \mu(I), \forall I$. For a given effort in R&D, the likelihood of a product being approved is the same, whatever its degree of dangerousness.

To sum up, two effects have to be distinguished: first, whatever the type of product, a higher investment in R&D increases the likelihood of a product being approved (i.e. $\mu_j{}'(I) > 0$, $\mu_j{}''(I) < 0$, $0 < \mu_j(I) < 1$, $\mu_j(I \to \infty) < 1$). Secondly, it is more likely for a safe product to be approved than a dangerous one (i.e. $\mu_S(I) \geq \mu_D(I)$, $\mu'_S(I) \geq \mu'_D(I), \forall I$).

As a consequence, the firm's expected profit under soft approval is:

$$E\left[\tilde{\Pi}^{AS}(I)\right] = [W_0].p(I).\Big(\varphi(I).\mu_S(I) + \big(1-\varphi(I)\big)\mu_D(I)\Big)$$
$$+[W].\Big(p(I).\Big(\varphi(I).\big(1-\mu_S(I)\big) + \big(1-\varphi(I)\big)\big(1-\mu_D(I)\big)\Big) + \big(1-p(I)\big)\Big) - k.I \quad (3)$$

with the subscript AS denoting "soft approval".

And under hard approval:

$$E\left[\tilde{\Pi}^{AH}(I)\right] = p(I).\varphi(I).\mu_S(I).[W_0] + p(I).\big(1-\varphi(I)\big).\mu_D(I).[W_0] - k.I \quad (4)$$

with the subscript AH denoting "hard approval".
In both cases, the firm's strategy is the same: when the new product is approved, whatever its real degree of dangerousness the firm has an interest in exploiting it because $W_0 > W$. The firm benefits from a higher efficiency, from the consumers' willingness to pay for the novelty and, additionally, from the "label effect": the public grant increases consumers' confidence in the (safeness of) the product, and their willingness to pay for the product increases. Recall that when only approval takes place, the firm does not internalize the risk of damage (which is totally borne by the consumers): the new product is always privately profitable for the firm. In case of non-approval, the firm has no alternative: to use the old product in case of soft approval, or to go bankrupt in case of hard approval.

The equilibrium levels of effort in R&D, I^{AS} under soft approval and I^{AH} under hard approval, are respectively defined by:

$$\frac{\partial E\left[\tilde{\Pi}^{AS}(I)\right]}{\delta I} = 0 \quad \text{under soft approval}$$

and

$$\frac{\partial E[\tilde{\Pi}^{AH}(I)]}{\delta I} = 0 \text{ under hard approval}$$

To evaluate the (expected) social impact of the firm's private decisions (see the next section), we need to define a function which reflects the social impact of the firm's decisions. So, let us define:

$$\begin{aligned}\mathrm{SI}^{AS}(I) = p(I).\big(\varphi(I).\mu_S(I)[W_0 - q_0 H] + (1-\varphi(I))\mu_D(I)[W_0 - q_1 H]\big) \\ +[W - qH].\Big(p(I).\Big(\varphi(I).\big(1-\mu_S(I)\big) + \big(1-\varphi(I)\big)\big(1-\mu_D(I)\big)\Big) + (1-p(I))\Big) - k.I\end{aligned} \quad (5)$$

Under soft approval, and

$$\mathrm{SI}^{AH}(I) = p(I).\varphi(I).\mu_S(I).[W_0 - q_0 H] + p(I).\big(1-\varphi(I)\big).\mu_D(I).[W_0 - q_1 H] - k.I \quad (6)$$

under hard approval.
Comparatively to the private expected profits, $E\big[\tilde{\Pi}^{AS}(I)\big]$ and $E\big[\tilde{\Pi}^{AH}(I)\big]$, these functions take into account the risk of damage borne by the consumers. But, as with the expected profits functions, decisions are made by the firm, which optimizes its own private expected profit. So, $\mathrm{SI}^{AS}(I)$ and $\mathrm{SI}^{AH}(I)$ determine the social impact (profit and risk of damage) on the private decisions (based on the expected profit only).
These functions differ from the function of social welfare $SW(I)$ in several ways. By nature, they differ because the decision maker does not have the same objective in both cases: social welfare is maximized by a benevolent planner who takes into account both the net benefit from operating and the risk of damage, while social impact functions (in this case of approval) only take into account the level of the risk of damage associated with a private decision which does not internalize this risk of damage. Secondly, they also differ because of the imperfection of the regulator: social welfare $SW(I)$ reflects a hypothetical situation in which the benevolent planner has all information at hand, and especially where he is able to detect the degree of dangerousness of the new product. He allows the diffusion of "safe" product, bans the "dangerous" ones, and so he is never wrong. The regulator of the "real" world has an imperfect degree of expertise, and can make errors. In particular, the expression $p(I).\big(1-\varphi(I)\big).\mu_D(I).[W_0 - q_1 H]$ in expressions (5) and (6) reflects the fact that the regulator can approve, wrongly, a dangerous product: this is a case of regrettable substitution.

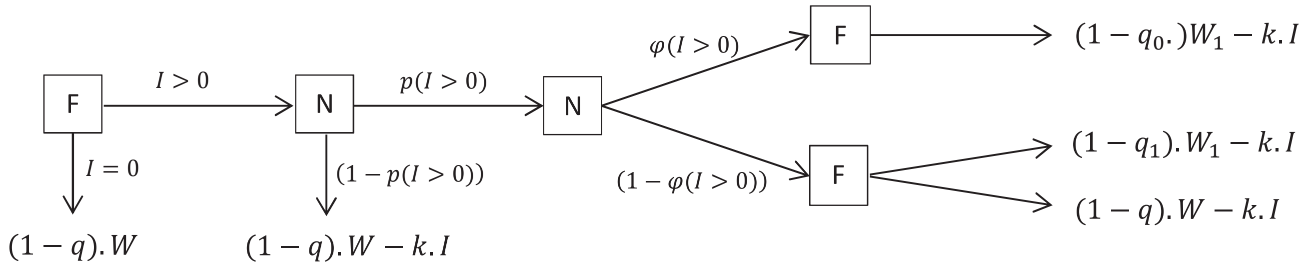
B. Civil liability

We only consider the case of *strict liability.*[7] Under such a liability rule, the firm is "automatically" held liable whenever an accident occurs, whatever its behavior or decisions. Moreover, the firm benefits from *limited liability,*[8] in the sense that its maximum payment in

[7] This kind of liability rule is increasingly used in cases of damage to the environment and/or to the health (see Ringleb and Wiggins, 1990).
[8] In the opposite case, liability is said to be *unlimited*: the value of harm in excess of the firm's wealth is borne by the firm's shareholders, out of their private pockets (see Jacob and Spaeter, 2014). Limited liability was

damages is limited to its net value: if the magnitude of harm exceeds the firm's wealth (as we suppose in this paper: $H > W_0$), the damages it has to pay are capped to its wealth. So the value of harm that exceeds the firm's wealth remains borne by the victims.

Figure 4. Decision tree (with civil liability private payoffs)



When successful R&D leads to a safe product, using the new product is a dominant strategy for the firm. When R&D is unsafe, it is not straightforward because the new product provides a higher net revenue but the probability of an accident (and so, bankruptcy) is higher. So the firm will be deterred from using the new (and dangerous) product if and only if:

$$(1-q_1).W_1 - k.I < (1-q).W - k.I$$
$$\Leftrightarrow W_1 < \frac{(1-q)W}{(1-q_1)} = \overline{W_1}$$

Only sufficiently small net operating revenues deter the firm from making a regrettable substitution. We suppose this situation to hold.

The firm's expected profit is:

$$E\left[\tilde{\Pi}^L(I)\right] = p(I).\varphi(I)[(1-q_0)W_1 - k.I] + \left[\left(1-p(I)\right) + p(I).\left(1-\varphi(I)\right)\right].[(1-q)W - k.I] \tag{7}$$

with the superscript L denoting liability.
I^{L*} satisfies:

$$\frac{\partial E\left[\tilde{\Pi}^L(I)\right]}{\partial I} = 0$$

The social impact of the firm's decisions can be represented by the following function:

$$SI^L(I) = p(I).\varphi(I)[W_1 - q_0 H] + \left[\left(1-p(I)\right) + p(I).\left(1-\varphi(I)\right)\right].[W - qH] - k.I \tag{8}$$

This function differs from the function $SW(I)$ in two ways. First, in case of discovery of a new and "safe" product, the firm cannot benefit from W_0 because of the lack of public label: it can only benefit from the novelty of the product but it cannot take value from benefiting from a public approval ($W_1 < W_0$). Secondly, as for the case of approval, the equilibrium

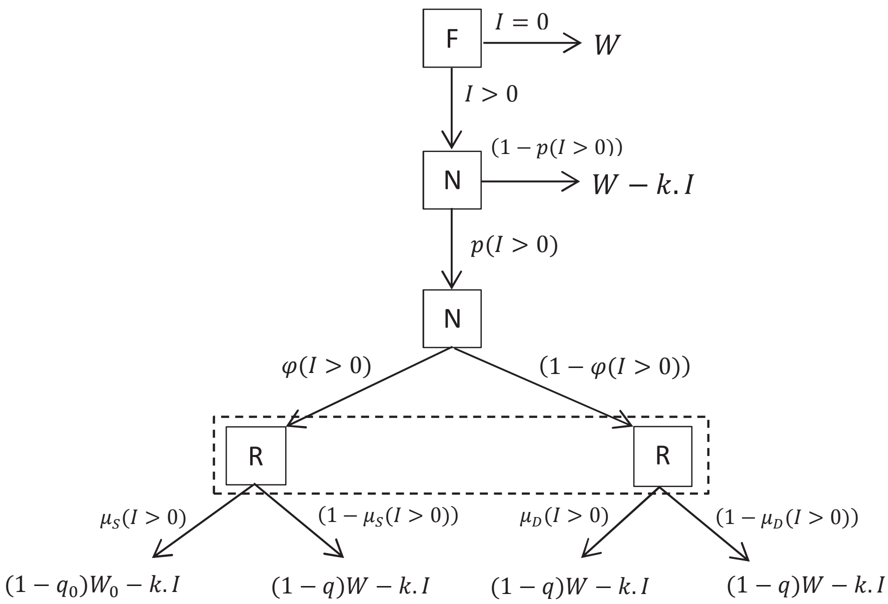
introduced during the 19th century to foster investment. It was called into question in the US during the 1980-1990s (see Alexander, 1992).

effort in R&D, I^{L*}, responds to the firm's optimization problem, which does not take into account the whole risk of damage borne by society.

C. Hybrid policy

In the following, we consider a combination of *ex ante* (soft) approval process and *ex post* civil liability. This kind of mixed policy can be represented by the following figure:

Figure 5. Decision tree (with technical approval and civil liability, private payoffs)



Under such a policy, the firm has both to present the new product (if any) before the public regulator to obtain the authorization to use it (but it can use the old product in case of failure, as under soft approval) and to pay damages to victims in case of accident. However, the firm still benefits from limited liability: it has only to pay up the net value of its assets (its profits cannot be negative), which is insufficient to compensate for the damage entirely ($W_0 < H$).

Note that when the new product is "safe" (with probability $\varphi(I)$), it is always a dominant strategy for the firm to exploit it when the regulator approves it. However, when the innovation is "dangerous" (with probability$(1-\varphi(I))$), there is *a priori* no such dominant strategy since the new product leads to an increase in the expected cost in damages. The firm's decision will depend on the additional revenues that the innovation can provide.
The firm chooses not to exploit an "approved but dangerous" product iff:

$$(1-q_1)W_0 - kI < (1-q)W - kI$$
$$\Leftrightarrow W_0 < \frac{(1-q)W}{(1-q_1)} = \overline{W_0} = \overline{W_1}$$

This net operating revenue threshold, below which the firm chooses not to proceed to a regrettable substitution, is the same as the one which prevails when civil liability is used alone. However, under a hybrid policy, because the firm benefits from a "public label" in case of (wrong) authorization, it is more likely for this condition not to be satisfied than under civil liability used alone. In the rest of the paper we assume this condition to be satisfied: *ex post* liability deters the firm from proceeding to a regrettable substitution.

The (private) problem the firm has to solve is:

$$E\left[\widetilde{\Pi}^{LA}(I)\right] = p(I).\varphi(I).\mu_S(I).[(1-q_0)W_0] + (1-p(I).\varphi(I).\mu_S(I))[(1-q)W] - k.I \tag{9}$$

with LA superscript denoting "liability and approval".
At equilibrium, the level of investment I^{LA*} satisfies:

$$\frac{\delta E\left[\widetilde{\Pi}^{LA}(I)\right]}{\delta I} = 0$$

Finally, the expected social impact of this policy is given by the following function:

$$SI^{LA}(I) = p(I).\varphi(I).\mu_S(I).[W_0 - q_0 H] + (1-p(I).\varphi(I).\mu_S(I))[W - qH] - k.I \tag{10}$$

Remark that this hybrid policy is a combination of soft approval and civil liability, and so it gathers benefits and disadvantages from both policies: comparatively to soft approval, the hybrid policy deters the firm from proceeding to a regrettable substitution thanks to the *ex post* liability. Comparatively to civil liability, the hybrid policy allows the firm to enjoy the benefits of the "public label" (W_0). But in case of a "not extremely competent" regulator ($\mu_S(I) \neq 1, \mu_D(I) \neq 0, \forall I$), the possibility for safe innovations to be wrongly banned reduces the social benefit of this policy.

Now that the different policies are introduced, we undertake a comparative analysis.

V. Comparative analysis

This section aims to propose a ranking of the different regulatory policies, relatively to the first-best situation.

In a first subsection, we theoretically compare *ex ante* policies (approvals) to the *ex post* one (civil liability). A second subsection provides numerical illustrations to assess how these conditions are restrictive or not. A third subsection is dedicated to the relative performance of the hybrid policy, and a fourth and final subsection provides a numerical analysis to highlight the impact of the regulator's degree of expertise on the ranking between policies.

1. Ex ante vs ex post policies: a theoretical analysis

Our demonstration requires the use of intermediate results, which we gather in the following Lemma.

Lemma 1

(i) For a given level of R&D, the welfare is higher under soft approval than under hard approval: $SI^{AS}(I) > SI^{AH}(I)$, I given.

(ii) In the absence of a label effect (i.e. $W_0 = W_1$), for a given level of R&D, the welfare is higher under civil liability than under soft approval: $SI^{L}(I) > SI^{AS}(I)$, I given and $W_0 = W_1$.

(iii) The simultaneous satisfaction of these two conditions:

$$W_0 - W_1 < qW - q_0 W_1$$

$$p(I)\varphi(I)\left(\mu'_s(I) - \mu'_D(I)\right) + p'(I)\mu_D(I) + p(I)\mu'_D(I) < [p'(I)\varphi(I) + p(I)\varphi'(I)]\left[1 - \left(\mu_s(I) - \mu_D(I)\right)\right]$$

is a sufficient condition for the private effort in R&D under soft approval, I^{AS*}, to be lower than the level of R&D under civil liability, I^{L*}.

(iv) Only a sufficiently myopic (i.e. $(\mu_S(I) - \mu_D(I)) \to 0$), stringent and insensitive (i.e. low level of $\mu_D(I)$, and $\mu'_D(I) \to 0$) regulator can provide less incentive for R&D under hard approval than under civil liability.

(v) I^{L*} is lower than the value of I which maximizes $SI^{L}(I)$.

(vi) The presence of an extremely competent regulator ensures I^{AS*} to be lower than the value of I which maximizes $SI^{AS}(I)$.

(vii) I^{LA*} is lower than the value of I which maximizes $SI^{LA}(I)$.

Proof: see in appendix.

The two conditions in point (iii) of Lemma 1 are easily interpretable: the first condition means the label effect (that the firm benefits from in case of successful approval) is lower than the expected decrease in damages the firm has to pay under civil liability when introducing a safer product. The second condition means that both the degree of the regulator's expertise, $\mu_s(I) - \mu_D(I)$, as well as the sensitivity of the probability of it granting approval, with respect to the effort in R&D, $\mu'_s(I)$ and $\mu'_D(I)$, must not be too high.
Then, we obtain the following theoretical results:

Proposition 1 On the comparison between decentralized policies, for a given environment ($\boldsymbol{W_0, W_1, W, q_0, q_1, H}$ given)

(i) A public intervention is socially desirable (*laissez-faire* is not desirable).

(ii) *Civil liability vs soft approval*: in the presence of an extremely competent Regulator, soft approval cannot dominate strict liability without a sufficiently significant label effect.

(iii) *Civil liability vs hard approval*: even in the absence of a label effect, only a sufficiently myopic and insensitive regulator can lead to hard approval not being preferred to civil liability.

Proof: see in appendix.

Proposition 1 point (ii) teaches us that, when comparing civil liability with soft approval, the presence of an extremely competent regulator is not (necessary) welcome. Such a result could seem counterintuitive at first glance, but it can easily be explained: an extremely competent regulator cannot be influenced by the level of effort I (he perfectly recognizes the types of products, whatever I). This lessens the marginal (private) impact of I, leading to a lower level of investment in soft approval than under civil liability. Only the perspective of an increase in the operating revenue thanks to the exploitation of the public label (and, so, only sufficiently high consumer willingness to pay for safety and trust in the public institutions) can lead for a preference for soft approval over civil liability.

In other words, a competent expert the consumers do not trust is not sufficient for soft approval to dominate civil liability: to "invest" in the credibility of the regulator is as important as investing in its competence.

Proposition 1 point (iii) highlights the strong incentivizing power of hard approval. Even in the absence of a label effect and in the presence of an extremely competent regulator (the decision of whom cannot be influenced by the level of effort in I), the level of induced investment under hard approval is always higher than that under civil liability. So, in addition to insensitivity to the level of investment (i.e. $\mu_S'(I) = \mu_D'(I) = 0$), only a sufficient degree of myopia could allow for $I^{AH*} < I^{L*}$ and, then, $SI^L(I^{L*}) < SI^{AH}(I^{AH*})$.[9]

Proposition 1 point (i) teaches us that a public regulation is more desirable than the absence of a public regulation (e.g. civil liability is preferred to *laissez-faire*). This result holds from the moment that the probability of getting a safe product (and so reducing the expected payment in damages) is sufficiently sensitive to the effort in R&D. Even if it is not obvious at first glance, this result differs from Immordino *et al.* (2011) who advocate *laissez-faire* when the likelihood of the new product being dangerous is sufficiently low. Two important differences between Immordino's analysis and ours have to be kept in mind. First, we assume the likelihood of all states of Nature to be endogenous (i.e. to depend on the firm's effort in R&D), while Immordino *et al.* (2011) consider the dangerousness of the new product to be exogenous. Moreover, in our case, there is always a problem of negative externality to regulate, in all states of Nature (a "safe" product is a product which is associated with a low probability of accident – it is not exempted from any possibility of causing an accident!). Immordino *et al.* (2011) consider instead that a "good" product is beneficial for all, the firm and Society: no negative externality is associated with the arrival of a "good" product. As a result, in Immordino *et al.* (2011), if the (exogenous) probability of being in the good state is sufficiently high, there is no need to enforce a public regulation which only reduces the firm's expected profit in the bad state of Nature. In our analysis, *laissez-faire* would be preferable to civil liability only in the case where the firm does not

[9] Nevertheless, this result has to be interpreted in the light of the assumptions we pose; and especially as regards the fact that profit falls to zero in case of non-approval (under hard approval). Two conflicting effects are present: first, the absence of firm diversification and the absence of a substitute for the commercialized product means the firm will die and means a relatively sharp decrease in consumers' utility in case of non-approval. This could lead to an underestimation of the welfare under hard approval. However, the prospect of the firm dying in case of non-approval provides it with very strong incentives for R&D. Knowing the probability of getting a safer product increases with the level of R&D effort, the likelihood of being in the good state of Nature is relatively high; and this could lead to an overestimation of the welfare under hard approval.

have the possibility, thanks to its effort in R&D, to "easily" modify the likelihoods of all states of Nature in a way to increase the chance of paying low damages in case of accident.

Now we analyze the effect of a variation in some parameters, and especially those associated with the risk of damage.

Proposition 2 On the impact of the risk of accident: approval processes *vs* civil liability

(i) The higher the value of q_1, the more desirable the use of civil liability relatively to all kinds of approval processes.

(ii) When the two conditions of Lemma 1 point (iii) are satisfied (i.e. when $I^{AS*} \leq I^{L*}$), then:

a. the lower the value of q_0, the more desirable the use of civil liability relatively to soft approval.

b. the higher the value of H, the more desirable the use of civil liability relatively to soft approval.

Especially, these two properties are met in the presence of an extremely competent regulator and without a label effect.

(iii) When the conditions mentioned in Lemma 1 point (iv) are satisfied, then the lower the value of q_0, the more desirable the use of civil liability relatively to hard approval.

(iv) The higher the value of H, the more desirable the use of hard approval when associated with an extremely competent regulator, relatively to the use of civil liability.

Proof: see in appendix.

Proposition 2 teaches us that a variation in the risk of accident associated with the use of the product has an influence on the relative ranking between the different decentralized policies. However, the *component* of the risk (probability, or damage) which varies is of paramount importance: all components do not have the same impact.

First, the higher the probability of accident associated with the introduction of a dangerous substitute, the more desirable civil liability over all kinds of approval processes. This result is essentially the consequence of the absence of any possibility for regrettable substitution (that we assume) when civil liability takes place.[10]

Secondly, the effect of a decrease in the probability of accident associated with the introduction of a "safe" substitute is less clear. It is favorable to civil liability (relatively to approvals processes) only in the cases where civil liability provides higher incentives for R&D

[10] This result is mainly the consequence of the assumption that civil liability prevents any regrettable substitution (i.e. $W_1 - W < q_1 W_1 - qW => W_1 < \frac{(1-q)W}{(1-q_1)} = \overline{W_1}$, the increase in net benefit from higher productive efficiency is lower than the increase in expected damages to pay when considering a new but more dangerous product). If the reverse situation holds, any increase in q_1 would also reduce the welfare under civil liability. Nevertheless, the perspective of facing higher expected damages in case of a new but more dangerous product would provide higher incentives for R&D, thus leading to a decrease in the level of risk (and so to an increase in welfare). This last effect would partially mitigate the first one.

than approval processes (this is especially the case when the regulator is sufficiently myopic and insensitive to the level of R&D provided by the firm).

Finally, the effect of an increase in the potential damage is complex to analyze. When comparing civil liability to soft approval, all cases in which civil liability provides higher incentives for R&D (including the case of an extremely competent regulator without a label effect) enhance civil liability when the magnitude of the potential damage increases. However, when we compare civil liability to hard approval, the situation is much less favorable to civil liability. Indeed, because of the ban on the initial product, only new and authorized products are introduced under hard approval (and can cause a damage of H); while civil liability allows for the introduction of a product in all states of Nature (successful R&D as well as unsuccessful R&D). In case of an extremely competent regulator,[11] hard approval allows only new and safe products to be introduced on the market: the risk of accident is the lowest possible, and so an increase in H has the lowest possible negative impact (relatively to other policies).[12]

In the following subsection, we investigate through numerical calculations whether the conditions highlighted above are, or not, restrictive ones

2. Ex ante vs ex post policies: a numerical illustration

The theoretical analysis has highlighted conditions for which an ex post policy (civil liability) is preferable to ex ante policies (approvals, hard and soft). However, because of the high degree of generality of our model, it is hard to see to what extent these conditions are restrictive or not. In order to investigate this issue, we perform numerical calculations.

We choose the following specifications and parameters.

Table 1. Parameters for numerical calculations

α	1	W_0	1040	q_0	0,01
β	1	W_1	1020	q_1	0,07
γ	0,8	W	1000	q	0,03
λ	0,2	k	2	H	10000

We have to find specifications for the probability functions, which meet all the theoretical properties we have posed. Taking the example of the probability function $p(I)$ we have to meet: $p'(I) > 0, p''(I) < 0, p(I = 0) = 0, p(I \to \infty) < 1$ (the other probability functions have the same requirements). The following specification meets all these requirements:

$$p(I) = 1 - exp^{(-\alpha.I)}$$

with $\alpha > 0$.

[11] Moreover, in the case of an extremely competent regulator, having $I^{AH*} > I^{L*}$ increases, under hard approval relatively to civil liability, the likelihood of the state “introducing a new and safe substitute”.

[12] As a last remark for points (ii) and (iii) of Proposition 2, we highlight only *sufficient* conditions for the relative desirability of civil liability to be improved. There could be other cases for which a variation in a parameter would favor civil liability over other policies but, given the degree of generality of our model, we only focus on sufficient conditions.

And so we adopt: $\varphi(I) = 1 - exp^{(-\beta.I)}$, $\mu_S(I) = 1 - exp^{(-\gamma.I)}$, $\mu_D(I) = 1 - exp^{(-\lambda.I)}$, with $\beta, \gamma, \lambda > 0$ and $\gamma \geq \lambda$ to ensure $\mu_S(I) \geq \mu_D(I)$ (recall that a strict inequality means the regulator has a positive degree of competence).
Given these specifications, we can consider that a value of γ equal to or higher than 5 (and a value of λ equal to 0) represents an extremely competent regulator (since, for $\gamma = 5$, a small investment in R&D ensures $\mu_S(I)$ to be close to 1. For instance $\mu_S(1) = 0{,}99$ for $\gamma = 5$). Recall that a myopic regulator is characterized by $\mu_S(I) = \mu_D(I), \forall I$: so $\gamma = \lambda$.

We also have to ensure that all assumptions are respected, as the fact that a new but more dangerous innovation is not socially desirable (the *statu quo* situation is preferred to a dangerous innovation). So, when giving numerical values to the different parameters we have to ensure that:

$$W_1 - q_1.H < W - q.H$$

And so the maximum value of W_1 is:

$$W + H.(q_1 - q)$$

With our numerical example, we now analyze the conditions for which ex post policy is preferable to ex ante policies.

Concerning the comparison between civil liability and soft approval, the theoretical analysis has shown that in the presence of an extremely competent regulator and in the absence of any label effect, civil liability is preferable to soft approval (Proposition 1, point (i)). Now we wonder: 1/ except for the case of an extremely competent regulator, what type of regulator still ensures that civil liability is preferable to soft approval in the absence of any label effect?; and 2/ given the presence of an extremely competent regulator, which magnitude of label effect is required for soft approval to dominate civil liability?

For the first question, we distinguish cases with a regulator having a positive degree of expertise, and cases of a myopic regulator.

Table 2. Cases in which the sufficient condition for civil liability to dominate soft approval does not hold

Positive degree of expertise ($\gamma > \lambda$) (pas=0,1)	Myopic regulator ($\gamma = \lambda$) (pas=0,1)
If $\lambda = 0,\ \gamma \in [0{,}1; 0{,}7]$ If $\lambda = 0{,}1,\ \gamma \in [0{,}2; 0{,}6]$ If $\lambda = 0{,}2,\ \gamma \in [0{,}2; 0{,}6]$ If $\lambda = 0{,}3,\ \gamma \in [0{,}3; 0{,}6]$ If $\lambda = 0{,}4,\ \gamma \in [0{,}4; 0{,}6]$	From 0,2 to 0,5

From these results, we can see that civil liability dominates soft approval (when no label effect exists) when the regulator's myopia is very conservative ($\gamma = \lambda < 0{,}2$) or when the myopia is sufficiently permissive ($\gamma = \lambda > 0{,}5$). Recall that myopia refers to the regulator's inability to distinguish between dangerous and safe products: $\mu_S(I) = \mu_D(I) = \mu(I)$, I given. In addition, two kinds of myopia can be distinguished: *conservative* myopia when the level of

$\mu(I)$ is low, and *permissive* myopia when the level of $\mu(I)$ is high. So, in case of conservative myopia the regulator is unable to distinguish between the different kinds of products and so it "easily bans" all of them, while in case of permissive myopia the regulator in unable to distinguish between the different kinds of products and so it "easily approves" all of them.
In case of "intermediate degree of myopia", the marginal sensitivity of the regulator to the investment in R&D (i.e. the value of $\mu'_S(I)$ and $\mu'_D(I)$) is sufficiently high for soft approval to provide higher incentives for R&D than civil liability.
Concerning the cases of positive degrees of expertise, soft approval provides higher incentives than civil liability when the probabilities of acceptance are low but very sensitive to the investment in R&D (which is the case of values of λ and γ between 0.1 and 0.6).

For the second question, given our parameters we find that the minimum value of W_0 above which soft approval provides higher incentives for R&D than civil liability is $W_0 = 1039$. Knowing that $W_1 = 1020$, we have a "label effect" of 19, which represents 1.9% of the operating revenue associated with the basic product.

Now we analyze the conditions for which hard approval is dominated by civil liability. The theoretical analysis has shown that the presence of an extremely competent regulator and the absence of a label effect lead both to $SI^L(I) > SI^{AH}(I), \forall I$ and to $I^{L*} < I^{AH*}$, so that it is impossible to determine the ranking between $SI^L(I^{L*})$ and $SI^{AH}(I^{AH*})$. In our illustration, the effect related to a higher level of investment (i.e. the probabilities of success - finding a "safer" product - being closer to 1) outweighs the effect associated with $SI^L(I) > SI^{AH}(I)$: hard approval dominates civil liability.[13] The theoretical analysis has shown there are sufficient conditions in which civil liability dominates hard approval. Now we question to what extent these conditions are (or not) restrictive ones.

Table 3. Cases in which the sufficient condition for civil liability to dominate hard approval hold

Positive degree of expertise ($\gamma > \lambda$) (pas=0,0001)	Myopic regulator ($\gamma = \lambda$) (pas=0,1)
If $\lambda = 0,\ \gamma \in [0{,}0001; 0{,}0006]$ If $\lambda = 0{,}0001,\ \gamma \in [0{,}0002; 0{,}6]$ If $\lambda = 0{,}0002,\ \gamma \in [0{,}0002; 0{,}0006]$ If $\lambda = 0{,}0003,\ \gamma \in [0{,}0003; 0{,}0006]$ If $\lambda = 0{,}0004,\ \gamma \in [0{,}0004; 0{,}0006]$ If $\lambda = 0{,}0005,\ \gamma \in [0{,}0005; 0{,}0006]$	From 0,0001 to 0,0006

Contrary to the comparison with soft approval, here we identify the cases in which the sufficient conditions for civil liability to dominate hard approval hold (in the preceding cases, we identify the cases in which the conditions did not hold).

[13] In that case, under hard approval we have: $I^{AH*} = 6{,}926$; $SI^{AH}(I^{AH*}) = 904{,}34$; $E[\pi^{AH}(I^{AH*})] = 1004{,}15$. Under civil liability: $I^{L*} = 3{,}657$; $SI^{AH}(I^{AH*}) = 901{,}48$; $E[\pi^{AH}(I^{AH*})] = 1000{,}46$.

These conditions are highly restrictive: the regulator has to have a very low level of expertise, and its (relative) myopia has to be very conservative for hard approval not to be preferred to civil liability.[14]

To sum up, there are conditions for civil liability to dominate soft approval, these conditions including conditions relative to the magnitude of the label effect and the degree of the regulator's expertise. Hence soft approval dominates civil liability when the magnitude of the label effect is sufficiently high (more than 1.9% in our illustration) and/or when the regulator is sensitive to the investment in R&D. However, in case of hard approval, the perspective of being "thrown out" of the market (when the approval is not granted) is sufficiently high for hard approval to dominate civil liability in the vast majority of cases (except for extreme cases of high conservative myopia of the regulator).

Now we turn to see to what extent the combination of ex ante and ex post policies can be desirable, before investigating in more detail the impact of the regulator's skills on the relative ranking of all the decentralized policies.

3. Combining *ex* ante and *ex* post policies: the case of the hybrid policy

Proposition 3 On the relative performance of the hybrid policy

(i) For a given regulator's degree of expertise and a given level of investment, we have: $SI^{LA}(I) > SI^{AS}(I) > SI^{AH}(I)$, I given.

(ii) At equilibrium, a necessary but not sufficient condition for hybrid policy to be socially preferable to soft approval is for the label effect not to be too significant (i.e. $SI^{LA}(I^{LA}) > SI^{AS}(I^{AS})$ requires $qW - q_0W_0 > 0$).

(iii) We cannot theoretically compare the social impacts of hybrid policy and hard approval since we have both $SI^{LA}(I) > SI^{AH}(I)$, I given, and $I^{AH*} > I^{LA*}$ in case of a non-myopic and non-insensitive regulator.

Proof: see in appendix.

Point (i) of Proposition 3 can be easily explained. For a given level of R&D, the superiority of soft approval over hard approval is explained by the absence of a ban on the old product in case of non-approval (recall that the old product is more dangerous than a new and safer product, but it is still socially desirable). The superiority of hybrid policy over soft approval is explained by the fact that the hybrid policy consists in combining soft approval with civil liability. Because civil liability prevents the firm from introducing a new but more dangerous product, the absence of any possibility for regrettable substitution

[14] Note that for most of these cases, the marginal benefit from R&D does not compensate for the marginal cost (k=2), so that the firm's optimal strategy under approval hard is not to invest and to withdraw from the market. We have to lessen the marginal cost of R&D to k=0,4 (or less) to allow a positive investment in R&D under hard approval to lead to a positive social-impact (but still lower than the one under civil liability).

leads hybrid policy to dominate soft approval (for a given level of R&D). The condition highlighted in Point (ii) can be explained by the following reasoning: from the firm's perspective, the main private benefit from R&D under soft approval is to obtain W_0 (i.e. to benefit from the public label) instead of W. In case of hybrid policy, this benefit is lessened due to the prospect of going bankrupt in case of accident (because of the payment in damages), but an additional benefit comes from the fact of benefiting from a lower probability of having to pay for damages. The lower the difference between W_0 and W, the lower the benefit from R&D under soft approval. However, even in the case where W_0 would be equal to W (no label effect), the ex post liability associated with the hybrid policy would provide incentives for R&D because of the prospect of decreasing the probability of having to pay in case of accident. By continuity (and considering additional elements linked to the regulator's probability of granting approval), there is a magnitude of the label effect below which the hybrid policy is preferable to soft approval.

Lastly, in order to see to what extent the regulator's degree of expertise has an impact on the ranking of all policies, we proceed to additional numerical calculations.

4. The effect of the regulator's expertise

Starting from the baseline scenario introduced above (see Table 1), we study the impact of changes in the levels and shapes of $\mu_S(.)$ and $\mu_D(.)$ functions (changes γ in and λ).

Result 1 On the impact of the regulator's degree of expertise on the relative ranking between the different policies

(i) The lower the value of $\mu_S(.)$, the more desirable the use of civil liability relatively to ex ante policies, $\mu_D(.)$ given and $W_0 > W_1$.

(ii) The higher the value of $\mu_S(.)$, the more desirable the use of ex ante policies (relatively to civil liability), $\mu_D(.)$ given and $W_0 > W_1$.

(iii) For given $\mu_S(.)$ and $W_0 > W_1$, $\mu_D(.)$ does not change the relative ranking between the different policies.

Result 1 teaches us that the regulator's degree of expertise has an influence on the relative ranking between the different policies (see Figure 7 in Appendix). However, the two components defining the level of expertise ($\mu_S(.)$ and $\mu_D(.)$) do not have the same impact: the relative ranking between the different policies is more sensitive to a variation in $\mu_S(I)$ (see Figure 6) than to a variation in $\mu_D(I)$ (see Figure 8 in Appendix).

Result 1 point (i) can be explained as follows: a decrease in the level of $\mu_S(.)$ leads to a decrease in the social impact of all ex ante policies (hard approval, soft approval and hybrid policy) but has no impact on civil liability (see Figure 6). As a consequence, below a certain threshold on the value of γ (which determines the level of $\mu_S(.)$), civil liability socially dominates ex ante policies. Two effects explain this feature: first, a decrease in $\mu_S(.)$ leads to a decrease in the likelihood of the best state of Nature occurring (i.e. introducing a safe substitute). Moreover, as highlighted in Figure 6 (see the second graph), a decrease in $\mu_S(.)$

means the regulator is more stringent: approval is less often granted for a given level of R&D. In response to this fact, firms provide a higher effort in R&D in order to get a higher likelihood of their new products being approved (see for $\gamma = 1$ and less). This is particularly salient with hard approval, for which the firm is engaged in a "survival strategy" (recall that without approval, its profit falls to zero). To sum up, such a conservative myopia leads to a "file effect": the firms increase their investment in R&D to provide the regulator with a thicker file, in order to increase the likelihood of getting approval; but such a high investment is not socially desirable. Note that for a very low value of γ (here, for 0.1 and less), the likelihood of getting approval is so low that firms choose the statu quo: they do not invest in R&D and keep using the old product (soft approval and hybrid policy). This "despondency effect" does not apply for hard approval because of the threat of zero profits.

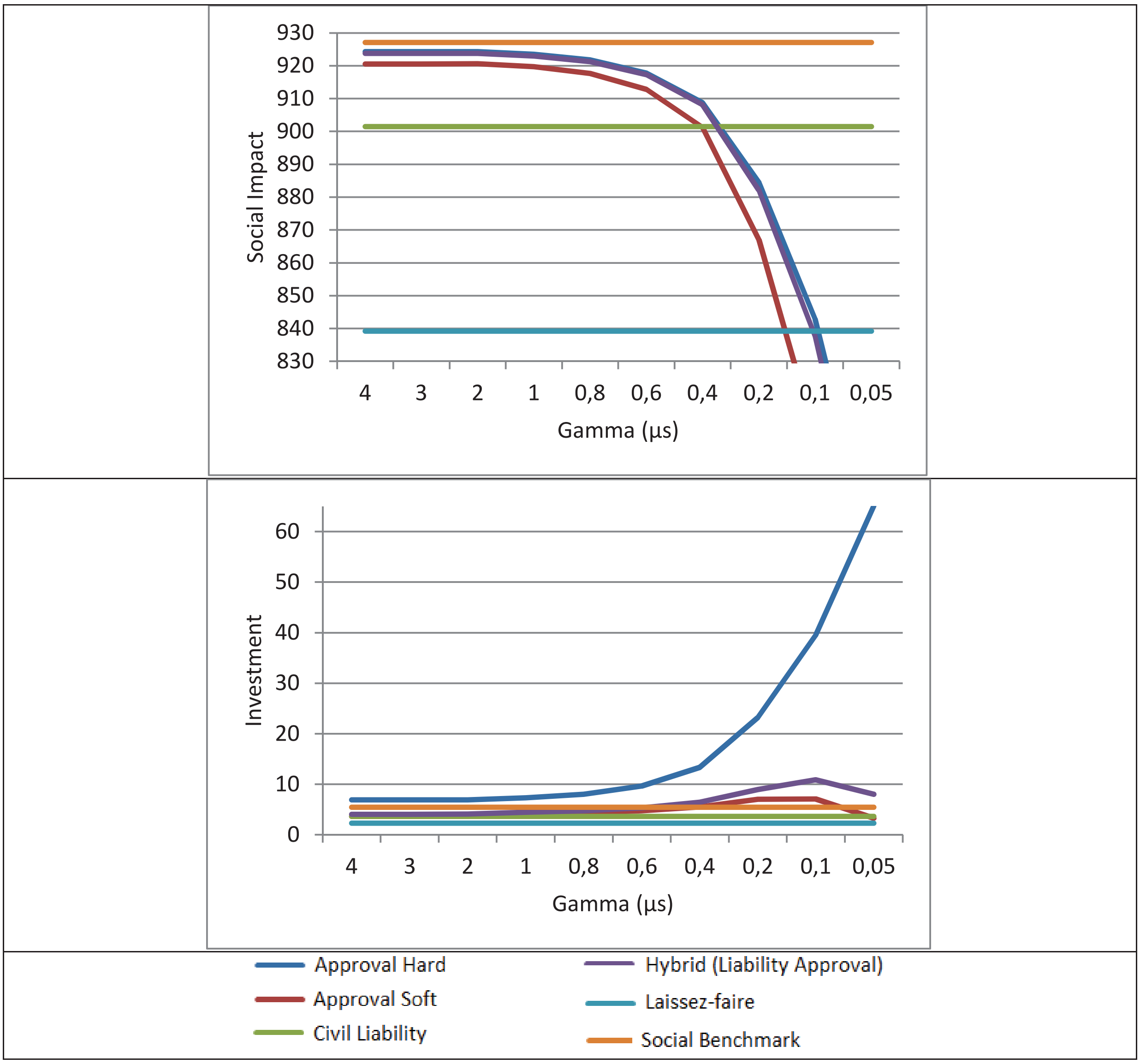
When the degree of the regulator's expertise increases (i.e. $\mu_S(.)$ increases, for a given $\mu_D(.)$), ex ante policies are relatively more desirable than civil liability. This result is essentially explained by the label effect, which both provides higher incentives to invest in R&D and leads to better satisfaction of consumers in the best state of Nature.[15]

About point (iii) of Result 1, an increase in $\mu_D(.)$ (or λ) leads to a permissive myopia: the regulator does not differentiate between the two kinds of substitutes (safe or dangerous), and "easily" approves both of them. Such a setup reduces the incentives to invest in R&D and, for a given level of R&D, reduces the social impact of ex ante policies because of the increase in the likelihood of introducing dangerous products; except for the hybrid policy (because the system of civil liability embedded in the hybrid system prevents any regrettable substitution). So, soft and hard approvals are impacted, hybrid to a lesser extent, and civil liability not at all. However, given our parameters, these impacts do not alter the ranking of the policies.

Finally, we remark that despite the fact that it is theoretically impossible to demonstrate that $SI^{AH}(I^{AH*}) > SI^{LA}(I^{LA*}) > SI^{AS}(I^{AS*})$ for $\mu_S(.)$ and $\mu_D(.)$ given, we observe this ranking in our simulations. Particularly focusing on the comparison between hard approval (AH), on one hand, and the two other ex ante policies on the other hand, we have theoretically demonstrated that, for a given level of R&D, AS and hybrid are socially preferable to AH, but the induced level of R&D is higher under AH than under other ex ante policies. Recall that a high level of R&D leads to a high likelihood of the best state of Nature (introducing a safer substitute). As a result, a high level of R&D can counteract a low-level function of social impact. This is the effect that we observe with hard approval: despite $SI^{AH}(.) < SI^{AS}(.) < SI^{LA}(.)$ for a given level of I, the high level of I^{AH*} leads, finally, AH to have a higher social impact than other ex ante policies (for a given regulator's expertise).

[15] Recall that, from Lemma 1 point (ii), in the absence of a label effect civil liability is preferable to soft approval for a given level of I.

Figure 6. Impact of the variation in $\mu_S(I)$ on the social impact and on the level of investment for the different policies ($\mu_D(I)$ with $\lambda = 0$ given and $W_0 > W_1$)



VI. Discussion and Conclusion

This paper deals with the issue of regulating products which can inflict harm on third parties (e.g. consumers). We focus on cases where the firms have the ability to engage in a R&D process, in order to develop substitutes for this (dangerous) product. The main question we address, for the public regulator, is to provide firms with optimal incentives to develop and market safer substitutes; knowing that innovation may lead to more dangerous new products (as highlighted by Tuncak (2013)). To this end, we compare the incentives provided by four policy tools: civil liability, approval (associated with a ban on the "old" product, or not), and a combination of civil liability and approval. The comparison between the different public policies is based on a welfare criterion, which takes into account the firm's expected profit, consumers' preferences and the level of the risk of harm.

We show that the ranking between the different policies is not frozen, and depends on different parameters such as: the skills of the regulator, the firm's ability to get value from the public label provided by approval processes, the characteristics of the risk of accident.

As key results, we show that an extremely competent regulator is not necessarily desirable because it provides less incentives for R&D than a less competent regulator, whose decision could be (a minima) driven by the intensity of the R&D effort. However, introducing a (public) label in which consumers trust can provide high incentives for R&D thanks to the prospects, for the firms, of being able to benefit from consumers' willingness to pay for safeness. The characteristics of the risk of accident are also important in the ranking: we show that the higher the probability of accident associated with the introduction of a dangerous substitute, the more desirable civil liability is relatively to all types of approval processes. Conversely, the higher the potential damage, the more desirable a process of approval associated with a ban on the old product.

Compared with Immordino *et al.* (2011), which was the first attempt to make a comparative analysis of several public policies aiming to regulate hazardous products, our results differ in several ways. First, Immordino *et al.* (2011) highlight a principle of increasing stringency of the public regulation as the probability of facing a dangerous product increases. But in our study, this probability is not exogenous and depends on the firm's effort in R&D. This effort being affected by the characteristics of the risk and of the regulation enforced, we do not find such an unchanging and progressive (in stringency) ranking. In particular, Immordino *et al.* (2011) find the absence of policy (i.e. *laissez-faire*) to be desirable in case of low probability of the new product being dangerous, while we find no such possibility (this could be the case only if we supposed the probability of getting a safer product to be very low and independent from the R&D effort). Secondly, the policies we compare are different (in their forms) to those outlined by Immordino *et al.* (2011): their "strict authorization" excludes the possibility of regrettable substitution; the possibility of banning the old product is excluded; and the "fines" system does not totally fit with civil (strict) liability since fines are conditional upon the regulator's ability to prove the dangerousness of the product. The comparison between our outputs is thus limited.

At first glance, our results could support some recent legislative changes in Europe, and especially in France. However, our results have to be interpreted in the light of the assumptions we pose. In particular, we highlight the fact that a ban on the old product provides the firms with high incentives to find substitutes. This policy was chosen by France in the case of bisphenol A (a ban on all food containers made with BPA was introduced in January 2015). While the incentivizing power of the ban is certainly high, we have to recall that this result is certainly overestimated because of the absence of diversification of the representative firm we consider (it is above all the prospect of bankruptcy which provides high incentives to make R&D efforts). We also underline the fact that approval processes are more efficient when public approval is "well identified" by consumers via, for instance, a system of public labeling which credibly guarantees consumers the high degree of safeness of the product. Such a system of public labelling is currently under debate in the French Parliament for firms which introduce safer substitutes to "chemical substances which are 'of concern'" (see the "Proposition de loi visant à intégrer le principe de substitution au régime juridique des produits chimiques,", "texte adopté" n°656, Assemblée Nationale, 14th of January, 2016). The first goal of this labelling project is to better inform consumers about the substances (or, the absence of substances) which are in the products they buy. But it is also obvious that such a system would also be enforced to encourage firms to develop safer alternatives, thanks to the prospect of increasing their earnings through a differentiation strategy.

An interesting extension of this work could be to take into account the possibility for the firms to make efforts to hide information on the type of the product they (want to) market. The recent scandal relative to Volkswagen's diesel engines highlights, in some cases, the firms' ability to hide information on the quality of their products (for a given degree of quality) in a way as to increase their chance to get public approval. Taking into account the possibility for the firms to make such efforts (in addition to make R&D efforts to increase the quality of products) could provide the public regulator with new insights on the optimal setting of decentralized policies, when those policies have to promote three "virtuous" behaviors: making R&D, not hiding information on (dangerous) products, and not marketing undesirable products.

Appendix

Proof of Lemma 1

Point (i)
The social impact associated with the use of soft approval is:

$$\mathrm{SI}^{AS}(I) = p(I).\big(\varphi(I).\mu_S(I)[W_0 - q_0 H] + \big(1-\varphi(I)\big)\mu_D(I)[W_0 - q_1 H]\big)$$
$$+[W - qH].\Big(p(I).\Big(\varphi(I).\big(1-\mu_S(I)\big) + \big(1-\varphi(I)\big)\big(1-\mu_D(I)\big)\Big) + (1-p(I))\Big) - k.I$$

The social impact associated with the use of hard approval is:

$$\mathrm{SI}^{AH}(I) = p(I).\varphi(I).\mu_S(I).[W_0 - q_0 H] + p(I).\big(1-\varphi(I)\big).\mu_D(I).[W_0 - q_1 H] - k.I$$

We can see: $\mathrm{SI}^{AH}(I) = \mathrm{SI}^{AS}(I) - \Big[[W - qH].\Big(p(I).\Big(\varphi(I).\big(1-\mu_S(I)\big) + \big(1-\varphi(I)\big)\big(1 - \mu_D(I)\big)\Big) + (1-p(I))\Big)\Big]$. Because of the ban in case of non-approval of the new product, the social impact associated with the use of hard approval is lower than the one under soft approval for a given level of I: $\mathrm{SI}^{AH}(I) < \mathrm{SI}^{AS}(I), I$ given.

Point (ii)
The social impact which is associated with the implementation of soft approval is:

$$\mathrm{SI}^{AS}(I) = p(I).\big(\varphi(I).\mu_S(I)[W_0 - q_0 H] + \big(1-\varphi(I)\big)\mu_D(I)[W_0 - q_1 H]\big)$$
$$+[W - qH].\Big(p(I).\Big(\varphi(I).\big(1-\mu_S(I)\big) + \big(1-\varphi(I)\big)\big(1-\mu_D(I)\big)\Big) + (1-p(I))\Big) - k.I$$

Under civil liability, the social impact is:

$$SI^L(I) = p(I).\varphi(I)[W_1 - q_0 H] + \big[\big(1-p(I)\big) + p(I).\big(1-\varphi(I)\big)\big].[W - qH] - k.I$$

Consider the case where there is no label effect under soft approval: $W_0 = W_1$. In that case, the difference $\mathrm{SI}^{AS}(I) - \mathrm{SI}^L(I)$, I given, can be written as:

$$p(I)\varphi(I)(1-\mu_S(I))[W_1 - q_0 H - (W - qH)]$$
$$+p(I)\big(1-\varphi(I)\big)\mu_D(I)[W - qH - (W_1 - q_1 H)] > 0$$

In that case, civil liability provides two social benefits (relatively to soft approval): first, it prevents wrongly refusing a safe new product (first line), and secondly it prevents any regrettable substitution in case of a dangerous new product (second line).

Point (iii)
Consider the FOC of I^{AS*} and I^{L*}. We have respectively:

$$\frac{\partial E\big[\tilde{\Pi}^{AS}(I)\big]}{\delta I} = 0$$

$\Rightarrow$

$$\begin{bmatrix} p'(I).\varphi(I).\big(\mu_S(I) - \mu_D(I)\big) \\ +p(I)\Big[\varphi'(I).\big(\mu_S(I) - \mu_D(I)\big) + \varphi(I).\big({\mu'}_S(I) - {\mu'}_D(I)\big)\Big] \\ +[p'(I).\mu_D(I) + p(I).{\mu'}_D(I)] \end{bmatrix} = \frac{k}{(W_0 - W)} \quad (11)$$

and

$$\frac{\partial E\left[\widetilde{\Pi}^{L}(I)\right]}{\partial I}=0$$

$$\Rightarrow [p'(I).\varphi(I)+p(I).\varphi'(I)]=\frac{k}{(1-q_0)W_1-(1-q)W} \quad (12)$$

When comparing (11) and (12), we can see that whatever the policy which applies, the marginal cost of R&D is always k. So, the level of I^{L*} is higher than that of I^{AS*} if and only if the marginal benefit from R&D is higher under civil liability than under soft approval. The marginal benefit of R&D under CL is:

$$[p'(I).\varphi(I)+p(I).\varphi'(I)][(1-q_0)W_1-(1-q)W]$$

and under AS:

$$\begin{bmatrix} [p'(I)\varphi(I)+p(I)\varphi'(I)]\big(\mu_S(I)-\mu_D(I)\big) \\ +p(I)\varphi(I).\left({\mu'}_S(I)-{\mu'}_D(I)\right) \\ +[p'(I).\mu_D(I)+p(I).{\mu'}_D(I)] \end{bmatrix}(W_0-W)$$

A sufficient condition to obtain $I^{AS*}<I^{L*}$ is to have:

$$(W_0-W)<[(1-q_0)W_1-(1-q)W]$$

And:

$$\begin{bmatrix} [p'(I)\varphi(I)+p(I)\varphi'(I)]\big(\mu_S(I)-\mu_D(I)\big) \\ +p(I)\varphi(I).\left({\mu'}_S(I)-{\mu'}_D(I)\right) \\ +[p'(I).\mu_D(I)+p(I).{\mu'}_D(I)] \end{bmatrix}<[p'(I).\varphi(I)+p(I).\varphi'(I)]$$

After some manipulations, we obtain the two conditions of point (iii).

Point (iv)

Consider the FOC of I^{AH*} and I^{L*}. For I^{AH*} we have:

$$\frac{\partial E\left[\widetilde{\Pi}^{AH}(I)\right]}{\delta I}=0$$

$\Rightarrow$

$$\begin{bmatrix} p'(I).\varphi(I).\big(\mu_S(I)-\mu_D(I)\big) \\ +p(I)\left[\varphi'(I).\big(\mu_S(I)-\mu_D(I)\big)+\varphi(I).\left({\mu'}_S(I)-{\mu'}_D(I)\right)\right] \\ +[p'(I).\mu_D(I)+p(I).{\mu'}_D(I)] \end{bmatrix}=\frac{k}{W_0} \quad (13)$$

And the FOC of I^{L*} is given by (12). We can see that whatever the policy which applies, the marginal cost of R&D is always k. So the level of I^{L*} is higher than that of I^{AH*} if and only if the marginal benefit from R&D is higher under civil liability than under soft approval. The marginal benefit of R&D under CL is:

$$[p'(I).\varphi(I)+p(I).\varphi'(I)][(1-q_0)W_1-(1-q)W]$$

and under AH:

$$\begin{bmatrix} [p'(I)\varphi(I) + p(I)\varphi'(I)]\big(\mu_S(I) - \mu_D(I)\big) \\ +p(I)\varphi(I).\left(\mu'_S(I) - \mu'_D(I)\right) \\ +[p'(I).\mu_D(I) + p(I).\mu'_D(I)] \end{bmatrix} W_0$$

As for point (iii) when comparing I^{L*} and I^{AS*}, we can compare the two elements of marginal benefits from R&D. Following this methodology, a sufficient condition to obtain $I^{AH*} < I^{L*}$ would be:

$$W_0 < [(1 - q_0)W_1 - (1 - q)W]$$

and:

$$\begin{bmatrix} [p'(I)\varphi(I) + p(I)\varphi'(I)]\big(\mu_S(I) - \mu_D(I)\big) \\ +p(I)\varphi(I).\left(\mu'_S(I) - \mu'_D(I)\right) \\ +[p'(I).\mu_D(I) + p(I).\mu'_D(I)] \end{bmatrix} < [p'(I).\varphi(I) + p(I).\varphi'(I)]$$

But the first condition is impossible by assumption.
So, only a sufficiently high difference between the second elements of marginal benefits could allow for $I^{AH*} < I^{L*}$. can be the case under the following two conditions: i/ when the regulator's degree of expertise is sufficiently low (myopic regulator): $\big(\mu_S(I) - \mu_D(I)\big) \rightarrow 0$, which implies $(\mu'_S(I) - \mu'_D(I)) \rightarrow 0$; ii/ when the regulator is sufficiently stringent and insensitive to the magnitude of the R&D effort: $\mu_D(I)$ is sufficiently low, $\mu'_D(I) \rightarrow 0$.

Point (v)
The value of I^{L*} is defined by (12). The value of I which maximizes $SI^L(I)$, eq (8), is given by:

$$\frac{\partial SI^L(I)}{\partial I} = 0$$
$$\Rightarrow [p'(I).\varphi(I) + p(I).\varphi'(I)] = \frac{k}{W_1 - W + H(q - q_0)}$$

Because of $W < W_1 < H$, this value of I is higher than I^{L*}.

Point (vi)
The value of I^{AS*} is defined by (11). The value of I which maximizes $SI^{AS}(I)$, eq (5), is given by:

$$\frac{\partial SI^{AS}(I)}{\delta I} = 0$$

$$\Rightarrow \begin{bmatrix} p'(I).\varphi(I).\left[\big(\mu_S(I) - \mu_D(I)\big).(W_0 - W) + \boldsymbol{\mu_S(I).H(q - q_0)} - \boldsymbol{\mu_D(I).H(q - q_1)}\right] \\ +p(I).\varphi'(I).\left[\big(\mu_S(I) - \mu_D(I)\big).(W_0 - W) + \boldsymbol{\mu_S(I).H(q - q_0)} - \boldsymbol{\mu_D(I).H(q - q_1)}\right] \\ +p(I).\varphi(I).\left[\left(\mu'_S(I) - \mu'_D(I)\right).(W_0 - W) + \boldsymbol{\mu'_S(I).H(q - q_0)} - \boldsymbol{\mu'_D(I).H(q - q_1)}\right] \\ +[p'(I).\mu_D(I) + p(I).\mu'_D(I)].[(W_0 - W) + \boldsymbol{H(q - q_1)}] \end{bmatrix} = k$$

All elements in bold are additional elements, relatively to the FOC of I^{AS*}. All are positive, except $H(q - q_1)$ in the last line. In a case of an extremely competent regulator, this last line disappears, so that the marginal benefits from R&D are higher when responding to $SI^{AS}(I)$ than when responding to $E\big[\widetilde{\Pi}^{AS}(I)\big]$: I^{AS*} is lower than the value of I which maximizes $SI^{AS}(I)$.

Point (vii)

The value of I^{LA*} is defined by:

$$\frac{\delta E\left[\widetilde{\Pi}^{LA}(I)\right]}{\delta I} = 0$$

$$\Rightarrow [p'(I).\varphi(I).\mu_S(I) + [\mu_S(I).\varphi'(I) + \mu_S{}'(I).\varphi(I)]p(I)] = \frac{k}{(1-q_0)W_0-(1-q)W} \quad (14)$$

The value of I which maximizes $SI^{LA}(I)$ is given by:

$$\frac{\partial SI^{LA}(I)}{\delta I} = 0$$

$\Rightarrow$

$$[p'(I).\varphi(I).\mu_S(I) + p(I).(\varphi'(I).\mu_S(I) + \varphi(I).\mu'_S(I))]\begin{bmatrix}(1-q_0)W_0 - (1-q)W \\ -\boldsymbol{q_0}(\boldsymbol{H}-\boldsymbol{W_0}) + \boldsymbol{q}(\boldsymbol{H}-\boldsymbol{W})\end{bmatrix} = k$$

All elements in bold are additional elements, relatively to the FOC of I^{LA*}. However, $-q_0(H-W_0) + q(H-W) > 0$: the marginal benefits from R&D are higher when responding to $SI^{LA}(I)$ than when responding to $E\left[\widetilde{\Pi}^{LA}(I)\right]$: I^{LA*} is lower than the value of I which maximizes $SI^{LA}(I)$.

Q.E.D

Proof of Proposition 1

Point (i)

It directly follows from points (ii), (iii), (v) and (vi) of Lemma 1. The absence of a label effect ensures $SI^L(I) > SI^{AS}(I)$ for a given level of I (Lemma 1, point (ii)). Comparing the FOC of I^{AS*} and I^{L*} (equations (11) and (12) respectively), the absence of a label effect ($W_0 = W_1$) and the presence of an expert regulator ($\mu_S(I) = 1, \mu_D(I) = 0, \mu_S{}'(I) = \mu_D{}'(I) = 0, \forall I$) ensure the marginal benefit from R&D to be higher under civil liability than under soft approval: $I^{L*} > I^{AS*}$ (Lemma 1, point (iii)). Knowing that I^{L*} and I^{AS*} are on the increasing part of $SI^L(I)$ and $SI^{AS}(I)$ respectively (Lemma 1 points (v) and (vi)), this is a sufficient condition to obtain: $SI^L(I^{L*}) > SI^{AS}(I^{AS*})$. Only a sufficiently large difference $W_0 - W_1 > 0$ ensures I^{AS*} to be higher than I^{L*} (and increases the level of $SI^{AS}(I)$ relatively to $SI^L(I), I$ given) to finally obtain $SI^L(I^{L*}) < SI^{AS}(I^{AS*})$.

Point (ii)

In the absence of a label effect ($W_0 = W_1$), by transitivity points (i) and (ii) ensure $SI^L(I) > SI^{AH}(I)$ for a given level of I. Moreover, Lemma 1 point (v) ensures that all possible values of I^{L*} are located on the increasing part of $SI^L(I)$. As a consequence, obtaining $SI^{AH}(I^{AH*}) < SI^L(I^{L*})$ only requires I^{AH*} to be lower than I^{L*}. A sufficient condition to obtain $I^{AH*} < I^{L*}$ is provided by Lemma 1 point (iv): only the presence of a sufficiently myopic and insensitive regulator leads civil liability to be preferable to hard approval (i.e. $SI^L(I^{L*}) > SI^{AH}(I^{AH*})$).

(Note that the FOC of I^{AH*} and I^{L*} (equations (13) and (12) respectively), allows us to check that even in the absence of a label effect ($W_0 = W_1$), an expert Regulator leads I^{AH*} to be higher than I^{L*})

Point (iii)

Laissez-faire simply consists in not applying public regulation: the firm does not internalize the risk of accident at all (the externality is not regulated).
Hence the private objective the firm has to maximize is:

$$\max_I E\left[\widetilde{\Pi}^{LF}(I)\right] = p(I).W_1 + \left(1 - p(I)\right).W - k.I$$

i.e. when the R&D is successful, the firm enjoys the new product without having to pay anything in case of accident and without having to get an ex ante authorization (so it earns W_1), and when R&D is not successful the firm can enjoy the basic product (W).
At equilibrium the amount of R&D, I^{LF*}, is such that:

$$\frac{\partial \Pi^{LF}(I)}{\partial I} = 0 \quad \Rightarrow \quad p'(I) = \frac{k}{W_1 - W}$$

with the subscript LF denoting laisser-faire.
The social-impact of LF is:

$$SI^{LF}(I) = p(I).(W_1 - \varphi(I)q_0H - (1 - \varphi(I))q_1H) + \left(1 - p(I)\right).(W - qH) - k.I$$
$$= p(I).\varphi(I).(W_1 - q_0H) + p(I).(1 - \varphi(I))(W_1 - q_1H) + \left(1 - p(I)\right).(W - qH) - k.I$$

It is straightforward to see that such a policy (or absence of policy) does not allow reaching the first-best situation.

Comparing with civil liability:

$$SI^L(I) = p(I).\varphi(I)[W_1 - q_0H] + \left[\left(1 - p(I)\right) + p(I).\left(1 - \varphi(I)\right)\right].[W - qH] - k.I$$

$W - qH > W_1 - q_1H$ ensures $SI^L(I) > SI^{LF}(I), \forall I$.
Recall that I^{L*} is such that:

$$[p'(I).\varphi(I) + p(I).\varphi'(I)] = \frac{k}{(1-q_0)W_1 - (1-q)W}$$

We have: $(1 - q_0)W_1 - (1 - q)W = W_1 - W - q_0W_1 + qW < W_1 - W$. As a consequence, the marginal benefit from R&D is not always higher under civil liability than under laissez-faire: it is not guaranteed to obtain $I^{L*} > I^{LF*}$, which would be a sufficient condition to obtain $SI^L(I^{L*}) > SI^{LF}(I^{LF*})$ (knowing that I^{L*} is always located on the increasing part of $SI^L(I)$. So, only a sufficiently sensitivity of the probability of getting a safe new product on the level of R&D (i.e. a sufficiently high value of $\varphi'(I)$) ensures civil liability to dominate laissez-faire.

Q.E.D

Proof of Proposition 2

Point (i)

First of all, recall that q_1 has no impact on the firm's effort in R&D, whatever the decentralized policy enforced (approvals do not allow for risk internalization, and civil liability, in our case, prevents any regrettable substitution).
Secondly, because civil liability prevents any regrettable substitution, the value of q_1 has no impact on the welfare associated with the enforcement of this policy (i.e. q_1 is not an argument of $SI^L(I)$, nor $SI^{LA}(I)$). So, a variation in q_1 only impacts the welfare associated with the use of ex ante approvals (used alone; i.e. q_1 is an argument of $SI^{AS}(I)$ and $SI^{AH}(I)$).

Taking the case of soft approval, recall that we have:

$$\text{SI}^{AS}(I) = p(I).\left(\varphi(I).\mu_S(I)[W_0 - q_0H] + (1-\varphi(I))\mu_D(I)[W_0 - q_1H]\right)$$
$$+[W - qH].\left(p(I).\left(\varphi(I).(1-\mu_S(I)) + (1-\varphi(I))(1-\mu_D(I))\right) + (1-p(I))\right) - k.I$$

And for hard approval we have:

$$\text{SI}^{AH}(I) = p(I).\varphi(I).\mu_S(I).[W_0 - q_0H] + p(I).(1-\varphi(I)).\mu_D(I).[W_0 - q_1H] - k.I$$

So we have:

$$\frac{\partial \text{SI}^{AS}(I)}{\partial q_1} = \frac{\partial \text{SI}^{AH}(I)}{\partial q_1} = -(1-\varphi(I))\mu_D(I)H < 0$$

Any increase in q_1 leads to a decrease in the welfare under approval policies, while the welfare under policies based on civil liability remains unchanged: this relatively favors civil liability against approvals.

Point (ii), part (a)

First of all, we compare the impact of a variation of q_0 on the welfare associated with civil liability and soft approval, for a given value of I. We have:

$$\frac{\partial \text{SI}^{AS}(I)}{\partial q_0} = -p(I)\varphi(I)\mu_S(I)H < 0$$
$$\frac{\partial \text{SI}^{L}(I)}{\partial q_0} = -p(I)\varphi(I)H < 0$$

It is easy to check that, for a given value of I, we have: $\frac{\partial \text{SI}^{L}(I)}{\partial q_0} < \frac{\partial \text{SI}^{AS}(I)}{\partial q_0} < 0$ because $\mu_S(I) < 1$. In the specific case of an extremely competent regulator, we obtain $\frac{\partial \text{SI}^{L}(I)}{\partial q_0} = \frac{\partial \text{SI}^{AS}(I)}{\partial q_0}$ because of $\mu_S(I) = 1, \forall I$. This means that in case of an imperfectly competent regulator, for a given level of I, any decrease in the value of q_0 leads to a higher increase in welfare (via a higher reduction in the risk of accident) under civil liability than under soft approval. In case of an extremely competent regulator, the effects are similar.

However, $p(I), \varphi(I)$ and $\mu_S(I)$ are all increasing with I. As a consequence, if I^{AS*} is sufficiently higher than I^{L*}, it is possible to have: $p(I^{AS*})\varphi(I^{AS*})\mu_S(I^{AS*}) > p(I^{L*})\varphi(I^{L*})$. In such a case, a decrease in q_0 would be more profitable under soft approval than under civil liability.

As a consequence, a sufficient condition for a decrease in q_0 to be more profitable under civil liability than under soft approval is to have $I^{AS*} \leq I^{L*}$, i.e. it is sufficient for the two conditions of Lemma 1 point (iii) to be satisfied. Note that the presence of an extremely competent regulator (and the absence of a label effect) is compatible with such a case, since $p(I^{AS*})\varphi(I^{AS*}) < p(I^{L*})\varphi(I^{L*})$ for $I^{AS*} < I^{L*}$, thus ensuring: $\frac{\partial \text{SI}^{L}(I^{L*})}{\partial q_0} < \frac{\partial \text{SI}^{L}(I^{AS*})}{\partial q_0}$.

Note also that satisfying these conditions ensures a sufficient condition for a decrease in q_0 to be more profitable under soft approval than under civil liability. This excludes some other compatible cases, since we have neglected an additional effect: a decrease in q_0 provides higher incentives in providing effort in R&D under civil liability (and not under soft approval). Indeed, recall that I^{L*} satisfies the following condition:

$$[p'(I).\varphi(I) + p(I).\varphi'(I)](1-q_0)W_1 - (1-q)W = k$$

It is obvious that a decrease in q_0 leads to an increase in the marginal benefit from R&D under civil liability, so that we obtain:

$$\frac{dI^{L*}}{dq_0} < 0$$

As a consequence, a decrease in q_0 provides higher incentives for R&D under civil liability and this, in return, leads to a decrease in the average level of risk of accident ($p'(I) > 0$, $\varphi'(I) > 0$ lead to a higher likelihood of the most desirable state of Nature, with safer product). To sum up, the total benefit following a decrease in q_0 when civil liability holds is:

$$\frac{d\mathrm{SI}^L(I)}{dq_0} = -p(I)\varphi(I)H$$
$$+[p'(I)\varphi(I) + p(I)\varphi'(I)]\frac{dI^{L*}}{dq_0}[W_1 - q_0H]$$
$$+\big[-p'(I) + p'(I)\big(1-\varphi(I)\big) - \varphi'(I)p(I)\big]\frac{dI^{L*}}{dq_0}[W - qH]$$
$$-k\frac{dI^{L*}}{dq_0}$$

As a result, having $I^{AS*} \leq I^{L*}$ (especially in the absence of a label effect and the presence of an extremely competent regulator) is a sufficient condition for a decrease in q_0 to be more profitable under civil liability than under soft approval, but by continuity there are some cases with $I^{AS*} > I^{L*}$ (I^{AS*} "slightly higher" than I^{L*}) which also allow for a decrease in q_0 to be more profitable to civil liability, because of the presence of additional (and cumulative) benefits through an increase in the level of R&D.

Following the same reasoning, part (b) is immediate. For a given level of I, the effects of a variation in H on $\mathrm{SI}^{AS}(I)$ and $\mathrm{SI}^L(I)$ are respectively:

$$\frac{\partial\mathrm{SI}^{AS}(I)}{\partial H} = -p(I)\big[\varphi(I)\mu_S(I)q_0 + \big(1-\varphi(I)\big)\mu_D(I)q_1\big]$$
$$- q\big[\big(1-p(I)\big) + p(I)\varphi(I)(1-\mu_S(I)) + p(I)(1-\varphi(I))(1-\mu_D(I))\big] < 0$$

And:

$$\frac{\partial\mathrm{SI}^L(I)}{\partial H} = -p(I)\varphi(I)q_0 - q\big[\big(1-p(I)\big) + p(I)(1-\varphi(I))\big] < 0$$

Because $\mu_S(I) < 1$ and $\mu_D(I) \neq 0$, we have: $\frac{\partial\mathrm{SI}^{AS}(I)}{\partial H} < \frac{\partial\mathrm{SI}^L(I)}{\partial H} < 0$: for a given level of I, an increase in H has a stronger negative impact on welfare under soft approval than under civil liability. Note that in the presence of an extremely competent regulator ($\mu_S(I) = 1, \mu_D(I) = 0, \mu'_S(I) = \mu'_D(I) = 0, \forall I$), we obtain $\frac{\partial\mathrm{SI}^{AS}(I)}{\partial H} = \frac{\partial\mathrm{SI}^L(I)}{\partial H}$.

Because of $p'(I) > 0$, $\varphi'(I) > 0$, $\mu'_S(I) > 0$ and $\mu'_D(I) > 0$ in the more general case, $\frac{\partial\mathrm{SI}^{AS}(I=I^{AS*})}{\partial H} < \frac{\partial\mathrm{SI}^L(I=I^{L*})}{\partial H}$ could not be satisfied for values of I^{AS*} sufficiently higher than I^{L*}. So, the satisfaction of the two conditions of Lemma 1 point (iii) is a sufficient condition to allow an increase in H to be less detrimental under civil liability than under soft approval.

Note that the case of the presence of an extremely competent regulator (and the absence of a label effect), allowing for $I^{L*} > I^{AS*}$, is compatible with $\frac{\partial \text{SI}^{AS}(I=I^{AS*})}{\partial H} < \frac{\partial \text{SI}^{L}(I=I^{L*})}{\partial H}$ since $p'(I) > 0$, $\varphi'(I) > 0$ and $q_0 < q$.

Point (iii)

We follow the same rationale as in Point (ii) part a.

The impact of a variation in q_0 on the welfare associated with civil liability and hard approval, for a given value of I. We have:

$$\frac{\partial \text{SI}^{AH}(I)}{\partial q_0} = -p(I)\varphi(I)\mu_S(I)H < 0$$

$$\frac{\partial \text{SI}^{L}(I)}{\partial q_0} = -p(I)\varphi(I)H < 0$$

It is easy to check that, for a given value of I, we have: $\frac{\partial \text{SI}^{L}(I)}{\partial q_0} < \frac{\partial \text{SI}^{AH}(I)}{\partial q_0} < 0$ because $\mu_S(I) < 1$. Any decrease in the value of q_0 leads to a higher increase in welfare (via a higher reduction in the risk of accident) under civil liability than under hard approval. In the presence of an extremely competent regulator we obtain: $\frac{\partial \text{SI}^{AH}(I)}{\partial q_0} = \frac{\partial \text{SI}^{L}(I)}{\partial q_0}$.

However, $p(I), \varphi(I)$ and $\mu_S(I)$ are all increasing with I. As a consequence, if I^{AH*} is sufficiently higher than I^{L*}, it is possible to have: $p(I^{AH*})\varphi(I^{AH*})\mu_S(I^{AH*}) > p(I^{L*})\varphi(I^{L*})$. In such a case, a decrease in q_0 would be more profitable under hard approval than under civil liability.

As a consequence, a sufficient condition for a decrease in q_0 to be more profitable under civil liability than under hard approval is to have $I^{AH*} \leq I^{L*}$, i.e. it is sufficient for the two conditions of Lemma 1 point (iv) to be satisfied (recall that, contrary to what prevails under soft approval, the presence of an extremely competent regulator without a label effect does not allow for $I^{AH*} < I^{L*}$).

However, this condition is a strong one because a decrease in q_0 provides additional benefits under civil liability (and not under hard approval): a decrease in q_0 provides higher incentives in R&D. Indeed, recall that I^{L*} satisfies the following condition:

$$[p'(I).\varphi(I) + p(I).\varphi'(I)](1 - q_0)W_1 - (1 - q)W = k$$

It is obvious that a decrease in q_0 leads to an increase in the marginal benefit from R&D under civil liability, so that we obtain:

$$\frac{dI^{L*}}{dq_0} < 0$$

As a consequence, a decrease in q_0 provides higher incentives for R&D under civil liability and this, in return, leads to a decrease in the average level of risk of accident ($p'(I) > 0$, $\varphi'(I) > 0$ lead to a higher likelihood of the most desirable state of Nature, with a safer product). To sum up, the total benefit following a decrease in q_0 when civil liability holds is:

$$\frac{d\text{SI}^{L}(I)}{dq_0} = -p(I)\varphi(I)H$$
$$+[p'(I)\varphi(I) + p(I)\varphi'(I)]\frac{dI^{L*}}{dq_0}[W_1 - q_0H]$$

$$+\left[-p'(I)+p'(I)\big(1-\varphi(I)\big)-\varphi'(I)p(I)\right]\frac{dI^{L*}}{dq_0}[W-qH]$$
$$-k\frac{dI^{L*}}{dq_0}$$

As a result, having $I^{AH*} \leq I^{L*}$ is a sufficient condition for a decrease in q_0 to be more profitable under civil liability than under hard approval, but by continuity there are some cases with $I^{AH*} > I^{L*}$ (I^{AH*} "slightly higher" than I^{L*}) which also allow for a decrease in q_0 to be more profitable to civil liability, because of the presence of additional (and cumulative) benefits through an increase in the level of R&D.

Point (iv)

For a given level of I, the effects of a variation in H on $\mathrm{SI}^{AH}(I)$ and $\mathrm{SI}^{L}(I)$ are respectively:

$$\frac{\partial \mathrm{SI}^{AH}(I)}{\partial H}=-p(I)\left[\varphi(I)\mu_S(I)q_0+\big(1-\varphi(I)\big)\mu_D(I)q_1\right]<0$$

And:

$$\frac{\partial \mathrm{SI}^{L}(I)}{\partial H}=-p(I)\varphi(I)q_0-q\left[\big(1-p(I)\big)+p(I)(1-\varphi(I))\right]<0$$

In case of an extremely competent regulator, we obtain:

$$\frac{\partial \mathrm{SI}^{AH}(I)}{\partial H}=-p(I)\varphi(I)q_0>\frac{\partial \mathrm{SI}^{L}(I)}{\partial H}=-p(I)\varphi(I)q_0-q\left[\big(1-p(I)\big)+p(I)\big(1-\varphi(I)\big)\right]$$

With $\frac{\partial \mathrm{SI}^{AH}(I)}{\partial H}<0, \frac{\partial \mathrm{SI}^{L}(I)}{\partial H}<0$

And recall that Lemma 1 point (iv) teaches us that the presence of an extremely competent regulator leads to: $I^{AH*} > I^{L*}$ (even in the absence of a label effect). Because of $p'(I) > 0$, $\varphi'(I) > 0$ we obtain: $\frac{\partial \mathrm{SI}^{AH}(I^{AH*})}{\partial H}>\frac{\partial \mathrm{SI}^{L}(I^{L*})}{\partial H}, \frac{\partial \mathrm{SI}^{AH}(I^{AH*})}{\partial H}<0, \frac{\partial \mathrm{SI}^{L}(I^{L*})}{\partial H}<0.$

Q.E.D

***Proof of Proposition 3*:**

Point (i)

From Lemma 1 point (i), we already know that: $SI^{AS}(I) > SI^{AH}(I)$, I given. We now have to show that: $SI^{LA}(I) > SI^{AS}(I)$, I given.

Comparing (5) with (10), we have:

$$\mathrm{SI}^{AS}(I)=p(I).\big(\varphi(I).\mu_S(I)[W_0-q_0H]+\boldsymbol{\big(1-\varphi(I)\big)\mu_D(I)[W_0-q_1H]}\big)$$
$$+[W-qH].\Big(p(I).\Big(\varphi(I).\big(1-\mu_S(I)\big)+\big(1-\varphi(I)\big)\big(1-\mu_D(I)\big)\Big)+(1-p(I))\Big)-k.I$$

And

$$SI^{LA}(I)=p(I).\varphi(I).\mu_S(I).[W_0-q_0H]+(1-p(I).\varphi(I).\mu_S(I))[W-qH]-k.I$$

The two social impact functions only differ in the fact that soft approval does not prevent regrettable substitution (bold expression); otherwise the two functions would be the same. As a consequence, we obtain: $SI^{LA}(I) > SI^{AS}(I)$, I given.

Point (ii)

From point (i) we already know that: $SI^{LA}(I) > SI^{AS}(I)$, I given. Lemma 1 point (vii) has shown that I^{LA} is always lower than the value which would maximize $SI^{LA}(I)$ and, under fair conditions, Lemma 1 point (vi) shows that I^{AS} is lower than the value which maximizes $SI^{AS}(I)$. As a consequence, equilibrium efforts in R&D are located on the increasing parts of $SI^{LA}(I)$ and $SI^{AS}(I)$. So, a sufficient condition to obtain $SI^{LA}(I^{LA}) > SI^{AS}(I^{AS})$ is to have: $I^{LA} \geq I^{AS}$. Comparing (14) and (11), we have:

I^{AS} satisfies:

$$\begin{bmatrix} p'(I).\varphi(I).\left(\mu_S(I) - \boldsymbol{\mu_D(I)}\right) \\ +p(I)\left[\varphi'(I).\left(\mu_S(I) - \boldsymbol{\mu_D(I)}\right) + \varphi(I).\left(\mu'_S(I) - \boldsymbol{\mu'_D(I)}\right)\right] \\ +[p'(I).\mu_D(I) + p(I).\mu'_D(I)] \end{bmatrix} = \frac{k}{(W_0 - W)}$$

And I^{LA} satisfies:

$$[p'(I).\varphi(I).\mu_S(I) + [\mu_S(I).\varphi'(I) + \mu_S{}'(I).\varphi(I)]p(I)] = \frac{k}{(1-q_0)W_0 - (1-q)W}$$

Recall that the marginal cost of R&D is k, and so other elements are related to the marginal benefit of R&D.

Comparing the left-hand sides of the two expressions, elements in bold tend to decrease the marginal benefit of R&D in AS relatively to LA, but the presence of the additional expression in the last line in the LHS of AS, $[p'(I).\mu_D(I) + p(I).\mu'_D(I)]$, does not allow us to form a ranking between these expressions. As a consequence, for the marginal benefit of R&D under LA to be higher than (or at least equal to) the one under AS, a necessary condition is to have: $(1 - q_0)W_0 - (1 - q)W > (W_0 - W) => qW - q_0W_0 > 0$

Point (iii)

We know from Point (i) that $SI^{LA}(I) > SI^{AH}(I)$, I given. However, if we compare the conditions which define I^{LA} (condition (14)) and I^{AH} (condition (13)) we find:

I^{AH} satisfies:

$$\begin{bmatrix} p'(I).\varphi(I).\left(\mu_S(I) - \boldsymbol{\mu_D(I)}\right) \\ +p(I)\left[\varphi'(I).\left(\mu_S(I) - \boldsymbol{\mu_D(I)}\right) + \varphi(I).\left(\mu'_S(I) - \boldsymbol{\mu'_D(I)}\right)\right] \\ +[p'(I).\mu_D(I) + p(I).\mu'_D(I)] \end{bmatrix} = \frac{k}{W_0}$$

And I^{LA} satisfies:

$$[p'(I).\varphi(I).\mu_S(I) + [\mu_S(I).\varphi'(I) + \mu_S{}'(I).\varphi(I)]p(I)] = \frac{k}{(1-q_0)W_0 - (1-q)W}$$

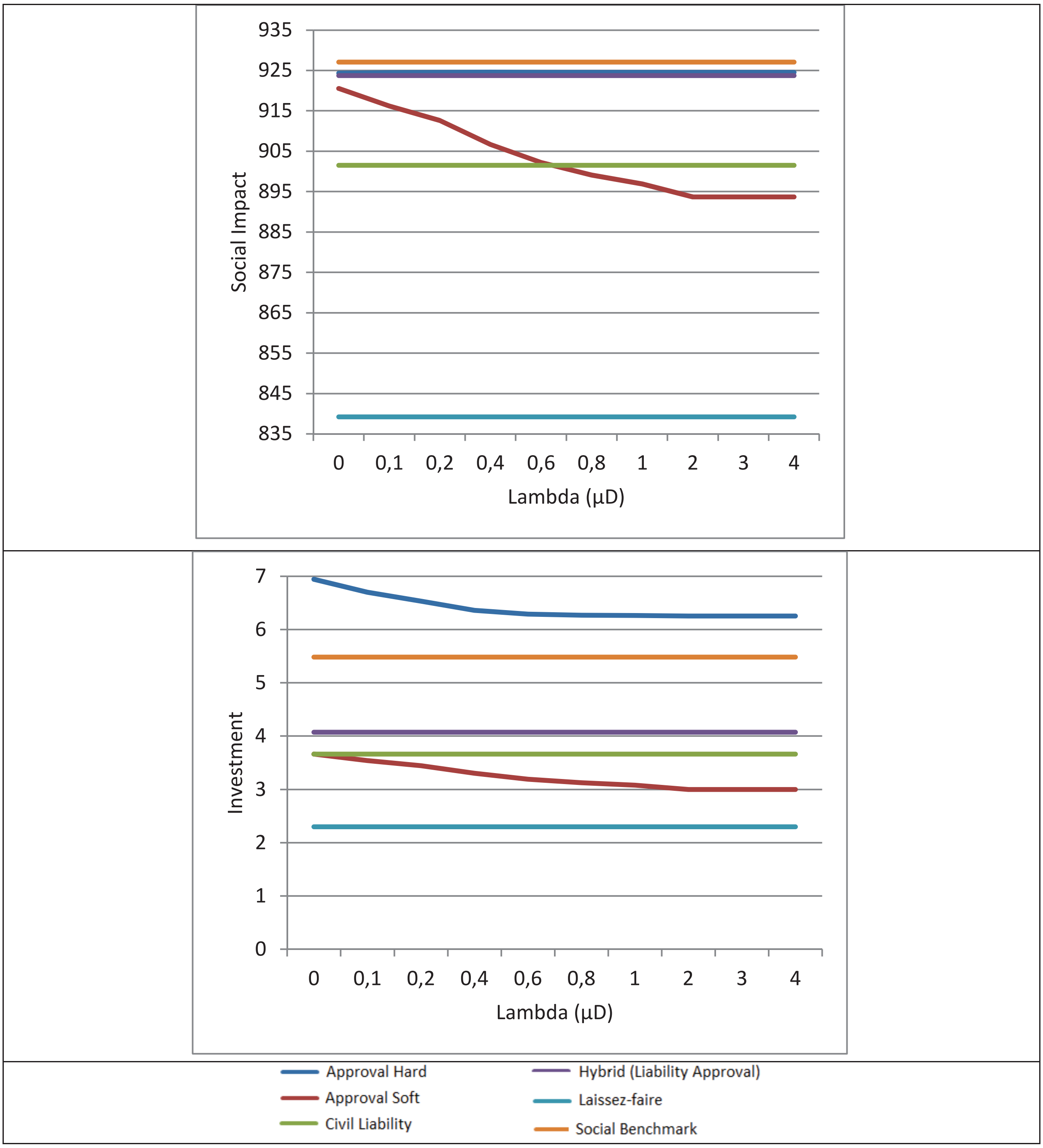
Having $W_0 > (1 - q_0)W_0 - (1 - q)W$ works in favor of $I^{AH} > I^{LA}$. However, from a purely theoretical point of view we cannot conclude that $I^{AH} > I^{LA}$ because of elements in bold, which tend to decrease the marginal benefit of R&D under AH relatively to LA. Hence, in the presence of an extremely myopic and insensitive regulator we could have $I^{AH} < I^{LA}$ but, for most cases of regulators having a positive degree of expertise, we obtain $I^{AH} > I^{LA}$.

Q.E.D

Figure 7. Impact of the regulator's degree of expertise on the relative ranking between the different policies

More desirable policy		Gamma (µs)	Gamma (µs)	Gamma (µs)	Gamma (µs)	Gamma (µs)	Gamma (µs)	Gamma (µs)	Gamma (µs)	Gamma (µs)	Gamma (µs)
		4	3	2	1	0,8	0,6	0,4	0,2	0,1	0,05
Lambda (µD)	0	Hard approval	Hard approval	Hard approval	Hard approval	Hard approval	Hard approval	Hard approval	Civil liability	Civil liability	Civil liability
Lambda (µD)	0,1	Hard approval	Hard approval	Hard approval	Hard approval	Hard approval	Hard approval	Hard approval	Civil liability	Civil liability	
Lambda (µD)	0,2	Hard approval	Hard approval	Hard approval	Hard approval	Hard approval	Hard approval	Hard approval	Civil liability		
Lambda (µD)	0,4	Hard approval	Hard approval	Hard approval	Hard approval	Hard approval	Hard approval	Hard approval			
Lambda (µD)	0,6	Hard approval	Hard approval	Hard approval	Hard approval	Hard approval	Hard approval				
Lambda (µD)	0,8	Hard approval	Hard approval	Hard approval	Hard approval	Hard approval					
Lambda (µD)	1	Hard approval	Hard approval	Hard approval	Hard approval						
Lambda (µD)	2	Hard approval	Hard approval	Hard approval							
Lambda (µD)	3	Hard approval	Hard approval								
Lambda (µD)	4	Hard approval									

Figure 8. Impact of the variation in $\mu_D(I)$ on the social impact and on the level of investment for the different policies ($\mu_S(I)$ with $\gamma = 4$ given and $W_0 > W_1$)



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