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Innovation and diffusion in risky industries under liability law: the case of "double-impact" innovations*

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Abstract

We suggest a model of innovation and diffusion of a new technology in which two firms, one innovative and one non-innovative, undertake risky activities that are regulated by liability rules. One originality of this study is to consider the presence of a "double-impact" innovation, impacting both the cost of risk prevention and the probability of accident. We compare strict liability and negligence in terms of incentives to innovate, to adopt the new technology and to prevent the risk. We find that the type of innovation and the behavior of the Regulator play key roles: when the Regulator acts as a "leader", a negligence rule is socially preferable if the innovation mainly impacts the cost of risk prevention. In other cases (Regulator as a "follower" and/or innovation with sufficiently high impact on the probability of accident), strict liability is preferable.

Keywords: Innovation, technological risk, strict liability, negligence.

JEL Classification: D81, K13, O31, Q55

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1 Introduction

In a broad sense, innovation could be defined as the process by which an agent raises (financial, physical, intellectual) resources to develop a new technology enabling him to increase the effectiveness of his effort in achieving his business, his goals. The "Oslo manual" (Org. of Eco. Coop. Dev (1997)) distinguishes *product technological innovation* from *technological process innovation*. In the last case, innovation is characterized by the "*implementation/adoption of new or significantly improved production or delivery methods. It may involve changes in equipment, human resources, working methods or a combination of these.*"[1]: innovation is a source of technological progress.

The economic analysis has early recognized the key role of technological progress (and so, the role of innovation); the technological progress being a key factor in the economic growth on the long term for Solow (1956). Starting from this point, a field of industrial economics tries to identify the best policy instruments (patents, prizes, research contracts, subsidies,. . .) to incite the firms to undertake innovation processes (research and development, R&D) in order to improve the efficiency of production capacities. Some studies points out some particular features of the R&D market that disrupt the optimal allocation of resources to innovation, especially the presence of *spillovers* (Arrow (1962), Hartwick (1984), d'Aspremont & Jacquemin (1988)).

The concept of *spillovers* refers to the positive externality inherent to the R&D process. Indeed the economic analysis defines innovation as a search for information research about new technologies. Thus, as a public good, some part of the information can be freely acquired by other agents on the market, thereby reducing the incentives to invest in R&D. Two kinds of spillovers are distinguished: the *input spillovers* refer to the externality that occurs during the research phase of the R&D process (exchanges between researchers from different firms,. . .); they benefit to other firms from the research sector (see Hartwick (1984), d'Aspremont & Jacquemin (1988), Helm & Schöttner (2008), Endres *et al.* (2008)). On the other hand the *output spillovers* refers to the ability of some

[1] See Org. of Eco. Coop. Dev (1997) p 8.

firms to imitate the innovation once it is developed (e.g. by using information contained in patents; see Martin (2002), Fischer *et al.* (2003)).

Later, the willingness to promote the technological progress (by providing incentives to R&D) has also become one of the main concerns for environmental economics. Following Kneese & Schultze (1975), a current of environmental economics focus on the role the technical progress can play in the regulation of pollutant effluents. More precisely, these studies analyze the incentives provided by different environmental policy tools (effluent taxes, abatement subsidies, emission permits,...) to develop and/or to adopt more efficient (i.e. with a lower marginal cost) abatement pollution technologies[2]. In this field, the more recent studies take also into account the specificities of the R&D market, notably 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)).
However, to our knowledge, before the contributions of Alfred Endres and co-authors (and more specifically Endres & Bertram (2006) and Endres *et al.* (2008)), the civil liability has not been recognized as a policy tool which can provide incentives to induced technological change[3], i.e. which can incite the firms to adopt and/or to design a new technology which permits to reduce more efficently a negative externality of production.

Following the seminal work of Calabresi (1970), Brown (1973) and Shavell (1980), the economic analysis of civil liability studies the role this legal instrument can play in the prevention of risks resulting from human activities. By setting a legal obligation to repair *ex post* the damage his activity can cause, the civil liability system provides *ex ante* incentives to an agent to reduce the risk of accident by applying prevention mea-

[2] Among the "classics" in the economic analysis of this question, we can cite Downing & White (1986) and Milliman & Prince (1989).

[3] In the frame of "product-risks", some studies focus on the incentives to invest in R&D to precise and/or to reduce a risk of accident (see Schwartz (1985), Viscusi & Moore (1993) Daughety & Reinganum (1995)). But they are not suitable to the analysis of (major) technological risks because they only consider "low" risks (no insolvency, except in Baumann *et al.* (2011)) and they focus on the relationship between firms and consumers: the latter have an influence on the profits of the former, while there exists no such interaction in the context of major technological risks.

sures (that can reduce the probability and/or the magnitude of the damage). Hence, these studies generally consider an agent who have to set an optimal (for him) level of prevention, say x, in order to minimize the sum of a cost of prevention, $c(x)$, and an expected cost of damages, $D(x)$, under the influence of the liability system. But the functions $c(.)$ and $D(.)$ are exogenously *given*. In the context of firms facing a technological risk, these studies thus leave out the possibility for the firms to undertake a technological change *via* the adoption or the development of a new and more efficient technology, characterized by *new functions* $c_2(.)$ and/or $D_2(.)$ with $c_2'(.) < c'(.)$, $D_2'(.) < D'(.)$. *A fortiori* these studies do not consider the role the liability system can play in terms of incentives to develop and/or to adopt a new technology of risk prevention.
That is why Alfred Endres and co-authors have begun a connection between the economic analysis of civil liability and the studies (in environmental economics) devoted to the incentives to promote technological change in the frame of pollutant emissions regulation. In the context of technological risk prevention, such a connection permits to consider the efficiency of liability rules and regimes in a broader point of view and, for instance, it permits to put into perspective the well-known inefficiencies of the limited liability[4] regime: considering a firm facing two available technologies, Jacob & Spaeter (2010) show that a firm, which is potentially insolvent in the case of an accident, can have incentives to adopt a new technology leading to lower probability and level of damage, thus permitting her to internalize the risk in full. This result should be considered in the light of the conclusions of Dari-Mattiacci & De Geest (2005): without the possibility to undertake such a technological change, they show that a firm which is potentially insolvent in the case of an accident has no incentives to adopt some measures that can reduce the magnitude of damage.

Nevertheless, this connection between law and economics and environmental economics is recent and it is necessary, in many extent, to complete the existing works.

First, Endres *et al.* (2008) compare two liability rules in terms of incentives to de-

[4]See e.g. Shavell (1986): in the presence of potential insolvency in the case of an accident (i.e. when the amount of damage exceeds the financial capacities of the firm), the limited liability regime externalizes a part of the cost of the risk. This may provide suboptimal incentives to prevent the risk.

velop a more efficient risk prevention technology, but the authors consider an industry composed of several symmetric firms, which have the same ability to undertake a R&D process. They focus on incentives to innovate by considering only innovative firms subject to *input* spillovers. Such a setup can lead to two remarks.

On the one hand, Endres *et al.* (2008) put aside the diffusion of the innovation to firms which have not the same ability in terms of R&D. But such a difference among firms is important: the possibility to diffuse an innovation to other firms (and earning some fees) can be one of the main motivation to innovate. Endres & Friehe (2011) consider the possibility to diffuse the innovation, but in a context that can not be applied to the study of technological risks (*nonpoint source pollution*).[5] Moreover, they consider that the maximal extent of the *output* spillovers is chosen by the innovative firm: contrary to what usually prevails in studies dealing with R&D (see e.g. Martin (2002)), the output spillovers are a decision variable and not an externality that the firm has to bear.

On the other hand, Endres *et al.* (2008) (as some studies in industrial economics: Hartwick (1984), d'Aspremont & Jacquemin (1988),. . .) consider *input* spillovers as a "curse" which discourage the firms to innovate. Nevertheless, some studies in innovation economics and economics of science consider input spillovers as a necessity to the success of R&D processes, which are costly, complicated and uncertain; this is not a barrier to innovation (see Dasgupta & David (1994), Diamond (1996), Callon (1999), Depret & Hamdouch (2009)). According to these authors, the design of an innovation need contributions coming from a multitude of different actors; the success of the R&D process is conditioned to the "good" combination of these different contributions. The input spillovers (called *knowledge* spillovers in these literatures) are thus a necessity during the research phase, permitting to carry out this necessary catalysis[6]. Far from being seen as a curse that automatically affects all innovative firms, the input spillovers

[5] Endres & Friehe (2011) consider two firms contributing to the same global pollution: it is impossible to determine the individual contributions to the global damage, so that the individual liabilities are arbitrarily determined. Hence, the pollution of one firm impacts the liability incumbant to the other firm: such an interaction is not compatible with technological risks.

[6] Some authors (Audretsch & Feldman (1996), Feldman (1999), Depret & Hamdouch (2009)) argue for a geographical proximity of these different actors in order to facilitate an organizational and cognitive connection between them, and thus to facilitate this catalysis. They distinguish the "world of science" from the "world of the technology", composed of firms wanting to impose their standards (Dasgupta & David (1994), Diamond (1996), Callon (1999)).

are a phenomenon that is necessary to bring out and maintain in a "world of science" (Dasgupta & David (1994)), composed of a multitude of complementary actors, whose interaction is a necessity to complete the innovation process.

Finally, we can remark that Endres *et al.* (2008), as in environmental economics, consider only innovations that permit to reduce the cost of applying prevention measures (or emissions abatement, in the context of pollution control). In this context, they compare two liability rules (strict liability and negligence) in terms of incentives to prevent a risk and to design a new (and more efficient) risk prevention technology. However, as we show in this paper, when studying civil liability as a mean to promote innovation, the type of innovation that can (potentially) be achieved is an essential feature. In the context of technological risk regulation, we can imagine that the technological progress leads to a reduction in applying risk prevention measures (as in Endres *et al.* (2008)), or leads to a higher efficiency of these measures in reducing the level of the risk, or even both of these properties. But, depending on the type of innovation that could be designed, we will show that the ranking of liability rules (concerning their objetives in terms of risk prevention and innovation) is different.

Finally, our study considers questions of innovation and technological diffusion, since we draw an economy composed by two firms having different ability in terms of R&D. Hence the "innovative firm" has the possibility to diffuse her innovation to the "non-innovative firm".

As in Fischer *et al.* (2003) and Endres & Friehe (2011), we consider the presence of *output* spillovers but, contrary to Endres & Friehe (2011), we see these kind of spillovers as a negative externality (as traditionally assumed: see Martin (2002), Fischer *et al.* (2003)). However, contrary to Endres *et al.* (2008), we do not consider *input* spillovers (during the research phase); their negative impact on the incentives to innovate being disputed by contributions in innovation economics and economic of science. So we focus our analysis on incentives problems located after the research phase.

Considering the pioneer work of Endres *et al.* (2008), we analyze the impact of strict liability and negligence in terms of incentives to prevent a risk of accident and to design a new (and more efficient) risk prevention technology. However we consider an innovation having a "double-impact" on the risk prevention technology: instead of only considering an innovation which permits to reduce the cost of applying risk prevention measures, we consider an innovation which also has an impact on the probability of accident. We show that the civil liability, as a mean to foster innovation, is sensitive to the type of innovation which can be designed. So we show that in the presence of a "cost-innovation" (having only an impact on the cost of prevention, not on the probability of accident) the negligence rule is preferable to strict liability. But the efficiency of the strict liability rule increases as the part of the technological progress that impacts the probability of accident becomes larger; strict liability is preferable when the innovation only permits to reduce the probability of accident.

The paper is organized as follows. Section 2 presents the assumptions and the social optimum. Sections 3 and 4 deal with the comparative analysis, and respectively present the case where the firms are subject to a strict liability rule and the case where they are subject to a negligence rule. Section 5 concludes and outlines avenues for future research.

2 A model of "double-impact" innovation

First, we present the assumptions of the model, then we present the schedule of decisions. This sections ends with an analysis of the socially optimal behavior, which will permit us to evaluate the relative efficiency of the different liability rules that we study in the next sections.

2.1 Basic assumptions

Consider a Society composed by two risk-neutral firms. These firms do not compet on the same output market. Nevertheless each firm conducts a risky activity, that can inflict a damage D to Society. More precisely we consider a unilateral risk of accident *between strangers* in the sense of Shavell (1980): the potential victims are unable to regulate the level of the risk they bear (we can think of people living close to chemical firms for instance). Consider that each firm is endowed with a default risk prevention technology, denoted A, which permits her to reduce the probability of accident $p_A(x)$ by applying risk prevention measures x ($\frac{\partial p_A(x)}{\partial x} < 0$, $\frac{\partial^2 p_A(x)}{\partial x^2} > 0$) for a cost $c_A(x)$ ($\frac{\partial c_A(x)}{\partial x} > 0$, $\frac{\partial^2 c_A(x)}{\partial x^2} > 0$).

However, one of the two firms can innovate (the firm denoted I). Hence, by investing an amount $e > 0$ in a R&D process, she can design a new technology, denoted B, that is more efficient than the technology A in two extents:

1/ technology B is more efficient than technology A in terms of a higher efficiency of the risk prevention measures in reducing the probability of accident ("safety-efficiency"): $\frac{\partial p_B(x,e)}{\partial e} < 0$, $\frac{\partial^2 p_B(x,e)}{\partial e^2} > 0$, $\frac{\partial^2 p_B(x,e)}{\partial x \partial e} < 0$, $p_B(x,+\infty) > 0$ $\forall x > 0$, $p_B(x,0) = p_A(x)$;

2/ technology B is more efficient than technology A in the sense that, with this new technology, it is less costly to apply risk prevention measures than with the technology A ("cost-efficiency"): $\frac{\partial c_B(x,e)}{\partial e} < 0$, $\frac{\partial^2 c_B(x,e)}{\partial e^2} > 0$, $\frac{\partial^2 c_B(x,e)}{\partial x \partial e} < 0$, $c_B(x,+\infty) > 0$ $\forall x > 0$, $c_B(x,0) = c_A(x)$.

We can remark that for $e = 0$, we have $p_B(x,0) = p_A(x)$ and $c_B(x,0) = c_A(x)$: technology B is identical to technology A, i.e. the absence of investment does not permit to improve the default technology. Hence we consider that technological progress is only the consequence of an investment in a R&D process: so we put aside the possibility of technological progress coming from activity or experience (*learning-by-doing*).

When a new technology B is obtained, the firm I has the possibility to freely patent her innovation and to sell it (licensing) to the other firm, NI (which can not innovate). Hence the firms are different regarding the output production, but they can use the same prevention technology. Such a setting may reflect, for instance, a situation in which the firms use the same input (a given chemical, e.g. nitrogen) but product different outputs (fertilizer, pesticide, ammonia,...). We suppose that the firm NI is unable to innovate, but it is able to imperfectly imitate the new technology by designing around the patent (thanks to the information contained this one). As a consequence, the firm NI has the ability to design a technology AB, more efficient than A but less efficient than B, characterized by:

$$p_{AB}(x) = \alpha p_B(x,e) + (1-\alpha)p_A(x) \tag{1}$$

$$c_{AB}(x) = \alpha c_B(x,e) + (1-\alpha)c_A(x) \tag{2}$$

The efficiency of the technology AB (safety-efficiency and cost-efficiency) is a linear combination of the efficiencies of technology A and technology B, and α is a coefficient which represents the absorption capacity of NI ($\alpha \in]0,1[$). This absorption capacity represents the ability of NI to absorb the output spillovers provided by the firm I: the higher α, the more NI is able to imitate the technology B (and the more AB is efficient).[7] So we obtain: $0 < p_B(x,e) < p_{AB}(x) < p_A(x) < 1$, $\frac{\partial p_B(x,e)}{\partial x} < \frac{\partial p_{AB}(x)}{\partial x} < \frac{\partial p_A(x)}{\partial x} < 0$, and $0 < c_B(x,e) < c_{AB}(x) < c_A(x)$, $\frac{\partial c_B(x,e)}{\partial x} < \frac{\partial c_{AB}(x)}{\partial x} < \frac{\partial c_A(x)}{\partial x} < 0$, x given.

Finally we suppose that there is no insolvency constraint: the firms are able to compensate the damage in full. In a context of large-scale risks, this may reflect the application of an unlimited liability regime, i.e. when the firms have to repair any damage whatever its magnitude[8]. We will discuss the implications of considering a limited liability regime at the end of the paper. Given the absence of insolvency constraint, that establishes some degree of independence between the incentives to produce and the incentives to prevent the risk, both the assumption of an additive damage D (independent of the level of activity) and a (simple) approach in terms of cost minimization can be made without loss of generality.

[7] This concept can be linked to the concept of *absorptive capacity* developed by Cohen & Levinthal (1990), but this latter is introduced in the presence of *input* spillovers and it depends on the past R&D experience of the firm (which benefits from the spillovers). Note that our concept of absorption capacity can be linked to the "performance" of the patent system: the more the system can be circumvented, the higher α.

[8] If the firm's financial capacity is insufficient to repair the damage, then shareholders' assets are requested to pay the remaining damages.

Now, before to begin our analysis, we have to introduce the schedule of decisions.

2.2 Schedule

In a first step, the firm I chooses the amount e to devote to R&D. For $e > 0$, a technology B is obtained with certainty[9] (if $e = 0$, there is no technological progress: only the technology A is available).

Then, the firm I offers her new technology B to the firm NI for a price Y. The firm NI has to choose between B and her alternative technology AB.

Finally, each firm chooses the level of prevention measures she wants to apply (x). The model is solved backward.

Now, we have to determine the socially optimal behavior (in terms of R&D, technological choice and risk prevention measures) before to compare the two liability rules (strict liability and negligence).

2.3 The social optimum

We consider the point of view of a public Regulator whose objective is to minimize the social costs of the activity of the two firms. We solve, by backward induction, the three step of the model from his point of view.

2.3.1 The optimal level of prevention

Consider a firm adopting the technology A. The socially optimal level of prevention x_A^* is solution of:

$$\begin{aligned} &\min_{x_A} c_A(x_A) + p_A(x_A)D \\ \Leftrightarrow &-\frac{\partial p_A(x_A)}{\partial x_A}D = \frac{\partial c_A(x_A)}{\partial x_A} \end{aligned} \tag{3}$$

[9]It is common to suppose a deterministic R&D process (see Endres *et al.* (2008), Endres & Bertram (2006), Fischer *et al.* (2003)). Even if such an assumption may not well represent the real R&D process, it simplifies the results without loss of generality (in such a comparative analysis).

The classical interpretation holds: the socially optimal level of prevention is set in a manner to equalize the marginal benefit of prevention (in terms of reduction in the expected cost of damage) to its marginal cost.

If a firm adopts the technology B, the optimal level of prevention x_B^* is solution of (for e given):

$$\min_{x_B} c_B(x_B, e) + p_B(x_B, e)D$$
$$\Leftrightarrow -\frac{\partial p_B(x_B, e)}{\partial x_B} D = \frac{\partial c_B(x_B, e)}{\partial x_B} \tag{4}$$

So, concerning the use of the technology B, the value of x_B^* depends on the amount e devoted to R&D.

Before to continue the analysis, we must clarify the "double dimension" of the optimal determination of the risk prevention technology, similarly to what exposed in Endres & Bertram (2006) and in Endres *et al.* (2008). As we usually observe in economic analysis of civil liability, the determination of the optimal risk prevention technology need to find an optimal level of prevention for *given* cost ($c(.)$) and probability ($p(.)$) functions. However, our analysis considers a second dimension in this problem in the sense that cost and probability functions are *not* given. Hence, optimal functions have to be determined *via* the search for an optimal level of effort in R&D (see later). As a consequence, for all $e = \hat{e} > 0$ that is *given*, leading to *given* $c_B(x, e = \hat{e})$ and $p_B(x, e = \hat{e})$ functions, there is an optimal level of prevention x_B^* as defined by (4), which permits to minimize the sum of the cost of the expected damage and the cost of prevention (related to the use of this technology B, with $e = \hat{e}$). However, considering all the technological possibilities that the investment in R&D permits to reach (i.e. considering the technology A and all technologies B that can be reached depending on the level of e), there exists only *one and unique* optimal level of prevention, x_B^{**}, that minimizes the sum of social costs of activity. This optimal level x_B^{**} is a best response to functions $c_B(x, e = e^*)$ and

$p_B(x, e = e^*)$, $e = e^* \geq 0$ being the optimal effort in R&D (see later). x_B^{**} verifies:

$$-\frac{\partial p_B(x_B, e = e^*)}{\partial x_B} D = \frac{\partial c_B(x_B, e = e^*)}{\partial x_B} \tag{5}$$

In other words, x_B^{**} is the optimal level of prevention when considering the functions $c_B(x, e)$ and $p_B(x, e)$ knowing $e = e^*$.[10] Hence (x_B^{**}, e_B^*) is the unique couple that permits to minimize the social cost of activity, given the set of all technological possibilities that can be reached by choosing x and e. Note that when $e^* = 0$, if the optimal technology is A and we obtain $x_B^{**} = x_A^*$.

2.3.2 The optimal technological choice

The use of a technology B is socially prefered to the use of the technology A[11] if and only if:

$$c_B(x_B^{**}, e^*) + p_B(x_B^{**}, e^*)D < c_A(x_A^*) + p_A(x_A^*)D \tag{6}$$

Given the properties of the technology B (safety-efficiency and cost-efficiency), its total diffusion is always socially desirable (from the moment that $e^* > 0$).

2.3.3 The optimal investment in R&D

The socially optimal investment in R&D solves the following problem:

$$\min_e 2[c_B(x_B^*, e) + p_B(x_B^*, e)D] + e$$

and we obtain e^* such that:

$$-2\frac{\partial c_B(x_B^*, e^*)}{\partial e} - 2\frac{\partial p_B(x_B^*, e^*)}{\partial e} D = 1 \tag{7}$$

[10] x_B^{**} is equal to x_B^* for the special case $e = e^*$.

[11] Recall that technology A corresponds to technology B for the special case $e = 0$.

Hence, the socially optimal level of investment in R&D is set so as to equalize the marginal benefit of R&D (in terms of reduction in the cost of applying a given level of prevention, and in terms of higher efficiency of the prevention in reducing the expected cost of damage) to its marginal cost.
Suppose that this condition is satisfied for a level $e = e^* > 0$. So the technology A has to be abandoned and replaced by the technology B.

Now that the optimal behavior is defined, we turn to the comparative analysis of the behaviors induced by two liability rules.

3 Behaviors under a strict liability rule

Under a strict liability rule, a firm is liable for all damage she can cause, whatever her behavior (in terms of prevention and/or innovation). The liability is "automatically" established, from the moment the damage is a consequence of the firm's activity. The firms' choices are the following.

3.1 Behaviors in terms of risk prevention

For some given $c_B(., e)$ and $p_B(., e)$ functions ($e > 0$ given), and in the absence of insolvency constaint, the economic analysis of civil liability[12] has early shown that the strict liability rule leads to socially optimal behaviors in terms of risk prevention ($x_B^{SL} = x_B^*$)[13]. Hence, private problem is the same as the social one, defined by (4).
Nevertheless, for the rest of the analysis, we have to distinguish two extreme cases:

1/ Case of a "cost-innovation": $\frac{\partial p_B(x,e)}{\partial e} = 0 \; \forall e$, $p_B(x, e) = p_A(x) = p(x)$:
Consider (4) with a function $p(x_B)$ instead of $p_B(x_B, e)$. We obtain:

$$-\frac{\partial p(x_B)}{\partial x_B} D = \frac{\partial c_B(x_B, e^*)}{\partial x_B} \tag{8}$$

$$-\frac{\partial p(x_B)}{\partial x_B} D = \frac{\partial c_B(x_B, e^{SL})}{\partial x_B} \tag{9}$$

[12]See e.g. Shavell (1980).
[13]The superscript SL indicates equilibrium values under strict liability.

(8) defines x_B^{**} and (9) defines x_B^{SL}, in the presence of a "cost-innovation". Recall that whatever $e > 0$, we obtain a technology B characterized by $0 < c_B(x, e) < c_A(x)$ et $0 < \frac{\partial c_B(x,e)}{\partial x} < \frac{\partial c_A(x)}{\partial x}$. Knowing that, in the special case of a cost-innovation, the function $p(.)$ is the same for both technologies, we obtain:

$$x_B^{SL} > x_A^{SL}$$

since the marginal cost of prevention is lower with the technology B (than with the technology A) while the marginal benefits are the same whatever the technology used. As a consequence, the new technology leads to a decrease in the expected cost of damages (i.e. $p(x_B^{SL})D < p(x_A^{SL})D$), but the evolution of the cost of risk prevention is uncertain: the sign of $c_A(x_A^{SL}) - c_B(x_B^{SL}, e^{SL})$ is undetermined since we have $c_B(x, e^{SL}) < c_A(x)$ (x given) and $x_B^{SL} > x_A^{SL}$ ($\forall\ e^{SL} > 0$).

2/ Case of a "safety-innovation": $\frac{\partial c_B(x,e)}{\partial e} = 0\ \forall e$, $c_B(x, e) = c_A(x) = c(x)$:
Consider (4) with a function $c(x_B)$ instead of $c_B(x_B, e)$. We obtain:

$$-\frac{\partial p_B(x_B, e^*)}{\partial x_B} D = \frac{\partial c(x_B)}{\partial x_B} \tag{10}$$

$$-\frac{\partial p_B(x_B, e^{SL})}{\partial x_B} D = \frac{\partial c(x_B)}{\partial x_B} \tag{11}$$

(10) defines x_B^{**} and (11) defines x_B^{SL}, in the presence of a "safety-innovation". For all $e > 0$ we obtain a technology B characterized by $0 < p_B(x, e) < p_A(x) < 1$ and $\frac{\partial p_B(x,e)}{\partial x} < \frac{\partial p_A(x)}{\partial x} < 0$. Knowing that, in the particular case of safety-innovation, the function $c(.)$ is the same for the two technologies, we obtain:

$$x_B^{SL} > x_A^{SL}$$

since the technology B provides a higher marginal benefit of prevention (than technology A) whereas the marginal cost of prevention is the same whatever the technology used. As a consequence, the new technology leads to a decrease in the expected cost in damages (i.e. $p_B(x_B^{SL}, e^{SL})D < p_A(x_A^{SL})D$), but it also leads to an increase in the cost of risk prevention because of $c(x_A^{SL}) - c(x_B^{SL}) < 0$.

In a wider setting, as defined in (4), in which the innovation impacts both the cost of risk prevention *and* the probability of accident, we can easily check that the technology B leads to an increase in the marginal benefit from prenvention (since $p_B(x,e) < p_A(x)$ and $\frac{\partial p_B(x,e)}{\partial x} < \frac{\partial p_A(x)}{\partial x}$, $e > 0$) *and* to a decrease in its marginal cost ($c_B(x,e) < c_A(x)$ and $\frac{\partial c_B(x,e)}{\partial x} < \frac{\partial c_A(x)}{\partial x}$, $e > 0$). This leads to $x_B^{SL} > x_A^{SL}$: the expected cost of damages is lowered but, as in the presence of a cost-innovation, there is an uncertainty concerning the evolution of the cost of prevention.

3.2 Behaviors in terms of technological choice

Whatever the investment $e > 0$ in R&D, a new technology B is available to the firm I, which can sell this new technology to the firm NI. However, as we said before, the firm NI is able to (imperfectly) imitate the innovation: thanks to the information available in the patent of the technology B (for instance), she is able to develop an alternative technology AB (designed "around the patent") that is more efficient than A but less efficient than B. As a consequence, the maximum selling price of the technology B, Y^{SL}, is such that:

$$E_{NI}[\tilde{C}_B^{SL}] = E_{NI}[\tilde{C}_{AB}^{SL}]$$
$$\Leftrightarrow c_B(x_B^{SL}, e^{SL}) + p_B(x_B^{SL}, e^{SL})D + Y^{SL} = c_{AB}(x_{AB}^{SL}) + p_{AB}(x_{AB}^{SL})D$$
$$\Leftrightarrow Y^{SL} = c_{AB}(x_{AB}^{SL}) - c_B(x_B^{SL}, e^{SL}) + D[p_{AB}(x_{AB}^{SL}) - p_B(x_B^{SL}, e^{SL})]$$

$E[.]$ is the expected value operator, $\tilde{C}$ is the (random) cost of activity of the firm. Knowing (1) and (2), we obtain:

$$Y^{SL} = Y^{SL}(\alpha) = (1-\alpha)(c_A(x_A^{SL}) - c_B(x_B^{SL}, e^{SL})) + D[(1-\alpha)(p_A(x_A^{SL}) - p_B(x_B^{SL}, e^{SL}))] \quad (12)$$

Note that for $\alpha = 1$ the firm NI is perfectly able to imitate the new technology: she has no willingness to pay for the technology B, the firm I is unable to sell her innovation ($Y^{SL}(\alpha = 1) = 0$). But we assume perfect information, so that the firm I can anticipate the firm's NI reaction to a given level of Y^{SL}: the firm I can fix the price at its maximum level, in a manner that the firm NI is indifferent between B and AB (in that case we suppose she buys B). Nevertheless, the threat of adopting an alternative technology AB prevents the firm I from appropriating the whole social benefits from her innovation, because she is unable to appropriate the whole benefit the firm NI derives from the adoption of B.

Again, we can distinguish the two extreme cases:

1/ Case of a "cost-innovation": $\frac{\partial p_B(x,e)}{\partial e} = 0 \ \forall e$, $p_B(x, e) = p_A(x) = p(x)$:
Consider (12) in the frame of this particular case. We can see that $D[(1 - \alpha)(p(x_A^{SL}) - p(x_B^{SL}))] > 0$, whereas the sign of $(1 - \alpha)(c_A(x_A^{SL}) - c_B(x_B^{SL}, e^{SL}))$ is unsure.

2/ Case of a "safety-innovation": $\frac{\partial c_B(x,e)}{\partial e} = 0 \ \forall e$, $c_B(x, e) = c_A(x) = c(x)$:
Consider (12) in this special case. We observe $D[(1 - \alpha)(p_A(x_A^{SL}) - p_B(x_B^{SL}, e^{SL}))] > 0$ and $(1 - \alpha)(c(x_A^{SL}) - c(x_B^{SL})) < 0$.

In a wider setting (as in (12)), we obtain conclusions that are similar to the specific case of a cost-innovation: the decrease in the expected damages $D[(1 - \alpha)(p_A(x_A^{SL}) - p_B(x_B^{SL}, e^{SL}))]$ leads to a higher willingness to pay for the new technology. However, the evolution of the cost of risk prevention is unsure, because the new cost function is lowered ($c_B(., e) < c_A(.)$) but the level of risk prevention measures is higher ($x_B^{SL} > x_A^{SL}$). Nevertheless, given the fact that the new technology is socially desirable, and knowing that strict liability leads to a full internalization of the risk (when there is no insolvency constraint), the decrease in expected damages offsets the (possible) increase in the cost of prevention: $Y^{SL}(\alpha)$ is positive from the moment that $\alpha < 1$.

Remark 1: *in the presence of a strict liability rule, for all α with $\alpha < 1$, when the new technology is available ($e^{SL} > 0$) she is diffused to the firm NI.*

3.3 Investment in R&D

Considering the two preceeding steps, the firm's I objective is:

$$\min_{e} c_B(x_B^{SL}, e) + p_B(x_B^{SL}, e)D - Y^{SL}(\alpha) + e$$

$$\Leftrightarrow \min_{e}(2-\alpha)c_B(x_B^{SL}, e) - (1-\alpha)c_A(x_A^{SL})$$

$$+D[(2-\alpha)p_B(x_B^{SL}, e) - (1-\alpha)p_A(x_A^{SL})] + e$$

At equilibrium the level of investment in R&D, e^{SL}, is such that:

$$-(2-\alpha)\frac{\partial c_B(x_B^{SL}, e^{SL})}{\partial e} - (2-\alpha)\frac{\partial p_B(x_B^{SL}, e^{SL})}{\partial e}D = 1 \quad (13)$$

Knowing that, whatever e, we have $x_i^{SL} = x_i^*$, we can state the following remark.

Remark 2: *in the absence of spillovers ($\alpha = 0$), the level of investment in R&D when a strict liability rule is in force is optimal ($e^{SL} = e^*$).*

But for all α such that $\alpha > 0$, we obtain $e^{SL} < e^*$ since the marginal benefit from R&D decreases in α. Considering (4) and knowing $\frac{\partial^2 p_B(x,e)}{\partial x \partial e} < 0$ and $\frac{\partial^2 c_B(x,e)}{\partial x \partial e} < 0$, we obtain $x_B^{SL} < x_B^{**}$.

Remark 3: *in the absence of spillovers ($\alpha = 0$), the level of risk prevention measures that is adopted when a strict liability rule is applied is optimal ($x_B^{SL} = x_B^{**}$). However, for all $\alpha > 0$, the level of risk prevention is lower than the optimum ($x_B^{SL} < x_B^{**}$).*

Regarding the two extreme types of innovation, we obtain:

1/ Case of a "cost-innovation": ($\frac{\partial p_B(x,e)}{\partial e} = 0$): e^{SL} such that $-(2-\alpha)\frac{\partial c_B(x_B^{SL}, e^{SL})}{\partial e} = 1$

2/ Case of a "safety-innovation": ($\frac{\partial c_B(x,e)}{\partial e} = 0$): e^{SL} such that $-(2-\alpha)\frac{\partial p_B(x_B^{SL}, e^{SL})}{\partial e} = 1$

For each case, the same remark prevails: in the absence of spillovers, strict liability is optimal. The presence of spillovers leads to a lower investment in R&D[14].

Gathering the statements of Remarks 1, 2 and 3, we obtain the following result.

[14]This can be checked by comparing the first-order conditions of e^{SL} relatively to (7), and by considering $\frac{\partial p_B(x,e)}{\partial e} = 0$ and $\frac{\partial c_B(x,e)}{\partial e} = 0$ for a cost-innovation and a safety-innovation respectively.

Proposition 1

(i) In the absence of spillovers, strict liability induces optimal behaviors.

(ii) When a strict liability rule is applied, from the moment that the innovative firm has an interest to innovate and that the absorption capacity of the non-innovative firm is not maximal($\alpha < 1$), the new technology is diffused (to the non-innovative firm).

Hence, in a different context than those adopted by Endres *et al.* (2008) (diffusion of the new technology, "double-impact" innovation), we find a similar conclusion: in the absence of spillovers, strict liability is optimal.

Following the same reasoning, we turn to analyze the behaviors in the presence of a negligence rule and to compare them with those previously obtained under strict liability.

4 Efficiency of the negligence: the Regulator and the type of innovation as key points

Contrary to what prevails under strict liability, under negligence the liability is established only if it is proved that the firm was negligent at the moment of the accident. In other words, it has to be proved before the Court that the firm, at the moment of the accident, failed to comply with a minimal standard of risk prevention. Hence, the scheme of liability is the following:

$$L(x_i, \bar{x}_i) = \begin{cases} 0 & if \quad x_i \geq \bar{x}_i \\ D & if \quad x_i < \bar{x}_i \end{cases}$$

$L(x_i, \bar{x}_i)$ is the amount of damages the firm has to pay in the case of an accident, depending on the level of risk prevention measures x_i and the minimal standard of prevention $\bar{x}_i$, previously determined by a Regulator, for the technology $i = A, B, AB$. We can observe that the firm is completely exempted from liability if she adopts a level of risk prevention measures higher or equal to the standard $\bar{x}_i$. In the opposite case, she is fully liable, as under strict liability.

In section 2, we have defined the specificity of our approach (introduced by Alfred Endres et co-authors), comparatively to what usually prevails in economic analysis of civil liability, in terms of "double dimension" in the definition of the optimal risk prevention technology. We have shown that the optimal behavior in terms of risk prevention does not only lie in the adoption of an optimal level of risk prevention measures, but it lies also in the choice of an optimal level of investment in R&D, leading to an optimal technology in the sense of *optimal cost and probability functions*. As a consequence, prevention measures (x) and R&D efforts (e) are linked. In the presence of a negligence rule, the role of the Regulator is reinforced: beyond his impact on the firms' behaviors in terms of risk prevention, the Regulator can, in some cases, have an influence on the incentives to undertake R&D. Depending on the fact that he takes this influence into account or not, we will make a distinction between a Regulator acting as a *leader* and a Regulator acting as a *follower*.

4.1 Behaviors in terms of risk prevention

In a first time, consider a Regulator acting as a *follower*: he ignores the relationship between risk prevention and innovation. To her mind, the application of the negligence rule could be defined by the following words: "For a given technology $(c_B(., e), p_B(., e))$, e given[15], there exists a level of prevention measures x_B^* that permits to minimize the social cost of activity. A firm who causes a damage will be held liable if and only if the level of prevention measures that was adopted at the moment of the accident is strictly inferior to the standard $\bar{x}_B$ defined by $\bar{x}_B = x_B^*$ (for this level of e)."

Given the absence of insolvency constraint, we have shown in section 3 that, for a given investment e in R&D, the level of prevention measures that is adopted by the firm under strict liability (x_B^{SL}) is equal to the level of prevention that minimize the social

[15]Recall that for $e = 0$ we obtain the technology A.

cost of the activity of the firm (x_B^*). Moreover, under a negligence rule, a firm that does not comply with the standard of prevention is held liable (in the case of an accident) in the same manner as under strict liability: in that case she has incentives to adopt $x_B = x_B^{SL}$ (for a given level of e). As a consequence, as shown by Shavell (1980), without insolvency constraint a firm always has an interest to adopt a standard of prevention equal to x_B^*: so we have $\bar{x}_B = x_B^* = x_B^{SL}$.

Remark 4: *for a given technology ($c_B(.,e)$, $p_B(.,e)$), e given, strict liability and negligence rule provide optimal incentives to risk prevention.*

4.2 Technological choice

Similarly to what prevails under strict liability, the maximal selling price Y^N of the technology B ($e > 0$) in the presence of a negligence rule is fixed in a manner that the firm NI is indifferent between buying the new technology B and adopting her own alternative technology AB. So we have:

$$E_{NI}[\tilde{C}_B^N] = E_{NI}[\tilde{C}_{AB}^N]$$
$$\Leftrightarrow c_B(\bar{x}_B, e^N) + Y^N = c_{AB}(\bar{x}_{AB}, e^N)$$
$$\Leftrightarrow Y^N = c_{AB}(\bar{x}_{AB}, e^N) - c_B(\bar{x}_B, e^N)$$

Considering (1) and (2) we obtain:

$$Y^N = Y^N(\alpha) = (1-\alpha)(c_A(\bar{x}_A) - c_B(\bar{x}_B, e^N)) \quad (14)$$

Comparatively to Y^{SL} (cf eq. (12)), the value of Y^N is independent of the magnitude D of the damage: when the firms comply with the standard of prevention, they benefit from an exemption from liability. As a consequence, the adoption of the new technology does not permit, from a private point of view, to benefit from a decrease in the cost of the risk. So the innovative firm can not include this benefit in the selling price. What is the impact of this property? We distinguish the two extreme types of innovation:

1/ Case of a cost-innovation ($\frac{\partial p_B(x,e)}{\partial e} = 0$, $\forall e$): in that case, the selling price $Y^N(\alpha)$ can be written as in (14). Knowing $\bar{x}_i = x_i^* = x_i^{SL}$ for a given technology $i = A, B$ (e given), and knowing $x_B^{SL} > x_A^{SL}$, the sign of $(c_A(\bar{x}_A) - c_B(\bar{x}_B, e^N))$ is unsure (because of $\bar{x}_B > \bar{x}_A$ and $c_B(x,e) < c_A(x)$, $e > 0$). If the new technology leads to an increase in the cost of prevention, the firm NI has no willingness to pay for this new technology.

2/ Case of a safety-innovation ($\frac{\partial c_B(x,e)}{\partial e} = 0$, $\forall e$): in that case we obtain $Y^N(\alpha) = (1-\alpha)(c(\bar{x}_A) - c(\bar{x}_B))$. Knowing $\bar{x}_B > \bar{x}_A$, the value of $Y^N(\alpha)$ is always negative: the firm NI has no willingness to pay for the new technology B.

In a wider frame, when the innovation has an impact on the cost of prevention and on the probability of accident, we obtain a result similar to the one obtained in the presence of a cost-innovation, since the cost of the risk is externalized (exemption from liability) and the innovation leads to a new function $c_B(., e) < c_A(.)$.

Remark 5: *when a negligence rule is applied, the diffusion of the new technology is not always possible. When the innovation only impacts the probability of accident (safety-innovation), the diffusion never occurs.*

4.3 Investment in R&D

Considering the two previous steps, the firm I's objective can be written as:

$$\min_e c_B(\bar{x}_B, e) - Y^N(\alpha) + e$$
$$\Leftrightarrow \min_e (2-\alpha)c_B(\bar{x}_B, e) - (1-\alpha)c_A(\bar{x}_A) + e$$

At equilibrium, the level of investment e^N is such that:

$$-(2-\alpha)\frac{\partial c_B(\bar{x}_B, e^N)}{\partial e} = 1 \tag{15}$$

By comparing (15) to (7), it is easy to check that the negligence rule can induce an optimal level of investment in R&D only in the presence of a cost-innovation ($\frac{\partial p_B(x,e)}{\partial e} = 0$,

$\forall e$) and when there is no spillovers.

If we consider an innovation having a "double-impact" (on the cost of prevention and on the probability of accident), a part of the social benefits from innovation is not internalized by the firms. When the firms comply with the standard of prevention $\bar{x}_i$, $i = A, B$, (and it is always the case here), the exemption from liability leads to an externalization of the cost of the risk. Relatively to its social benefit, the private benefit from adopting a more efficient risk prevention technology is reduced. This brings suboptimal incentives to invest in R&D.
To illustrate, consider the extreme case where the innovation is only a safety-innovation (i.e. $\frac{\partial c_B(x,e)}{\partial e} = 0$, $\forall e$). In the previous subsection we have observed that $Y^N(\alpha) < 0$: the non-innovative firm has no willingness to pay for the new technology B. Knowing that the innovative firm has an interest to comply with the standard of prevention in order to be exempted from liability in the case of an accident, her objective function is:

$$\max_e W - c(\bar{x}_B) - e$$

We know that the level of prevention $x_B^{SL} = x_B^*$ increases with the level of investment e (see subsection 3.3). Knowing $\bar{x}_B = x_B^*$ for a given effort e in R&D, it follows that the severity of the standard of prevention $\bar{x}_B$ strenghtens with the degree of technological advancement. As a consequence, from a private point of view, undertaking R&D in the presence of a safety-innovation under a negligence rule is only synonymous with an increase in the cost of risk prevention: the exemption from liability externalizes all the social benefit from innovation. Incentives to innovate are null ($e^N = 0$), the two firms keep the technology A. Hence, the negligence rule can provide optimal incentives to R&D in the presence of a cost-innovation (and without spillovers), but it can also provide no incentives at all in the presence of a safety-innovation.

In a wider framework, in the presence of a double-impact innovation, suboptimality of the negligence rule increases with the relative weight of the "safety-impact" of the innovation (i.e. the importance of $|\frac{\partial p_B(x,e)}{\partial e}|$), comparatively to its "cost-impact" (i.e. $|\frac{\partial c_B(x,e)}{\partial e}|$).

The more important the safety-impact, the more e^N deviates from e^*, and the more the technology $(c_B(.,e^N), p_B(.,e^N))$ is suboptimal. It follows a higher gap between $\bar{x}_B$ (i.e. the level of x_B^* associated to e^N) and x_B^{**} (i.e. the level of x_B^* associated to e^*) since x_B^* increases in e. Moreover, for given level of investment e and cost-impact $|\frac{\partial c_B(x,e)}{\partial e}|$, the level of the corresponding x_B^* increases with the safety-impact of the innovation: the likelihood to obtain $c_B(\bar{x}_B, e^N) - c_A(\bar{x}_A) < 0$ is more important, leading to $e^N = 0$.

However, for a given absorption capacity α, strict liability permits the firm to take into account the two benefits from innovation: it follows $e^S > e^N$, and x_B^{SL} (x_B^* associated to e^{SL}) higher than $\bar{x}$ (x_B^* associated to e^N). Strict liability induces behaviors that are closer from social optimum than negligence, so we can state:

Proposition 2 *Assume that a negligence rule holds, and the Regulator acts as a "follower".*

(i) Incentives to innovate are optimal only in the presence of a cost-innovation, and in the absence of spillovers; in that case strict liability and negligence are both optimal.

(ii) In all other cases (i.e. with a double-impact innovation or a safety-innovation), strict liability induces more innovation and prevention than negligence: strict liability is socially preferable to negligence.

Proof: see Appendix. ♦

Hence, our analysis joins those of Endres *et al.* (2008) in the sense that, in the presence of a cost-innovation, strict liability and negligence are equivalent: they are optimal if there are no spillovers, and they lead to levels of investment and prevention that are inferior to the optimum when there are spillovers. However, contrary to Endres *et al.* (2008), our analysis shows that the suboptimality of the negligence becomes worse when the part of the technological progress that impacts the probability of accident (safety-impact) is high.

Now, we turn to analyze in what extent the Regulator's behavior can affect the efficiency of the negligence rule.

4.4 Negligence and the Regulator as a leader

Before continuing our analysis, let us return to the behaviors (of the firm I) in terms of innovation depending on the liability rule in force. The socially desirable behavior, e^*, can be discribed by (7):

$$-2\frac{\partial c_B(x_B^*, e^*)}{\partial e} - 2\frac{\partial p_B(x_B^*, e^*)}{\partial e}D = 1$$

When a strict liability rule is applied, the level of investment e^{SL} (eq. (13)) is such that:

$$-(2-\alpha)\frac{\partial c_B(x_B^{SL}, e^{SL})}{\partial e} - (2-\alpha)\frac{\partial p_B(x_B^{SL}, e^{SL})}{\partial e}D = 1$$

Under a negligence rule, e^N (eq. (15)) is such that:

$$-(2-\alpha)\frac{\partial c_B(\bar{x}_B, e^N)}{\partial e} = 1$$

We can remark that, when the part of technological progress impacting the probability of accident is negligible (i.e. $\frac{\partial p_B(x,e)}{\partial e} \to 0$), these three conditions are close, especially the conditions relative to strict liability and negligence. As a consequence, in the presence of a innovation that *mainly* impacts the *cost* of prevention, we have to check if, in our context, the result highlighted by Endres *et al.* (2008) can applied or not.

In their analyze, Endres *et al.* (2008) show that, in the presence of several and identical firms who are subject to *input* spillovers and in the presence of an innovation that only impacts the cost of prevention, a negligence rule may be socially preferred to a strict liability rule *from the moment that the Regulator takes into account the relationship between the firm's decision in terms of prevention (x) and the firm's decision in terms of innovation (e).* Considering our framework, we can also imagine a Regulator taking a position of *leader*: instead of taking as given the firm I's investment decision and to set the standard of prevention for a given technology $(c_B(.,e),\ p_B(.,e))$ (e given), he could adopt a position of *leader*[16] and fix an *only* standard, regardless of the level of investment e. With such a behavior, he could indirectly impose the level of investment in R&D. Endres *et al.* (2008) show that fixing a standard of prevention to a level that is *slighlty higher than the level of prevention that would prevail under strict liability* incites the firms to increase their investment in R&D, thus leading to a decrease in the social cost of activity: negligence is thus socially preferable to strict liability (see Endres *et al.* (2008), Proposition 4).

If the mechanism highlighted by Endres *et al.* (2008) can be applied to our context (with asymmetric firms), the negligence rule could be socially preferable to strict liability in the presence of a cost-innovation. However, as the technological progress also impacts the probability of accident (and when the relative importance of this impact becomes higher), it is less likely that negligence can be preferable to strict liability: under negligence, the externalization of the benefits from innovation in terms of reduction in the cost of the risk (lower expected damage) leads to lower incentives to invest in R&D (relatively to strict liability). If the level of investment in R&D is lower under negligence than under strict liability, then the level of risk prevention measures is also lower under negligence than under strict liability: given $\frac{\partial^2 p_B(x,e)}{\partial x \partial e} < 0$ and $\frac{\partial^2 c_B(x,e)}{\partial x \partial e} < 0$, we know that the technology $(c_B(.,e^N),\ p_B(.,e^N))$ is characterized both by a lower marginal benefit and a higher marginal cost of risk prevention than the technology $(c_B(.,e^{SL}),\ p_B(.,e^{SL}))$ if $e^N < e^{SL}$. Considering our framework, we study the implications related to the presence of Regulator acting as a leader. We obtain the following result.

Proposition 3 *Consider a set of technological possibilities* $(c_B(.,e),\ p_B(.,e))$*, and assume that the effort* e *in R&D has an impact on both the cost of prevention (cost-impact,* $|\frac{\partial c_B(.,e)}{\partial e}| \neq 0$*) and the probability of accident (safety-impact,* $|\frac{\partial p_B(.,e)}{\partial e}| \neq 0$*).*

There exists a threshold value of the safety-impact of R&D, $|\frac{\partial p_B(.,e)}{\partial e}|$*, relatively to*

[16] *Leader* and *follower* terms are directly related to the Stackelberg's game. Indeed the Regulator who is a follower is a follower in the sense of Stackelberg: he defines the standard of prevention *after* the firm's decision in terms of R&D, thus taking this decision as a given parameter. The firm (the leader) chooses the level of e as a best response to the Regulator's reaction in terms of determination of the standard.

its cost-impact, $|\frac{\partial c_B(.,e)}{\partial e}|$, *below which a negligence rule is socially preferred to a strict liability rule. Beyond this threshold value, strict liability is socially preferable.*

Proof: see Appendix. ♦

Let us detail the methodology of this proof. In a first step (point 1/ of the proof) we have to ensure that, in the presence of a negligence rule, a higher investment in R&D (beyond the level that would prevails under strict liability) leads to a decrease in the social cost of activity. Then (point 2/), we have to check if it is possible (and under what conditions) to provide more incentives to innovate, under negligence than under strict liability, by fixing a standard of prevention the level of which is *slightly higher than the level that would prevails under strict liability.* Finally (point 3/), we have to ensure that fixing a higher standard of prevention (than the strict liability level) leads to a decrease in the social cost of activity.

Synthesising these three points, this Proposition shows that when the innovation *mainly impacts the cost of prevention* (low impact on the probability of accident), we find, in our context, the result highlighted by Endres *et al.* (2008): a Regulator, acting as a *leader*, can induce more investment in R&D by applying a negligence rule. To reach this result the Regulator has to fix a standard of prevention the level of which is *slightly*[17] *higher than the level that would prevails under strict liability.* And this permits to reduce the social cost of activity.

However, when the impact of the technological progress on the probability of accident is too important (relatively to its impact on the cost of prevention), the difference between the two liability rules in terms of incentives to invest in R&D is too high. As a consequence, it is impossible for a firm to adopt a standard of prevention the level of which is higher than the level of prevention that would prevail under strict liability: such a level of risk prevention measures is too costly to adopt given the degree of technological

[17]"*Slightly*" *higher* in the sense that the Regulator has to ensure that the firm I has an interest to adopt this higher level of risk prevention (in order to benefit from the exemption from liability). Otherwise, if the firm does not comply with the standard the situation is similar to strict liability.

advancement that it is possible to reach under negligence (depending on the incentives to R&D provided by this rule). In the presence of such a "double-impact" innovation (with a high impact on the probability of accident), the mechanism highlighted by Endres *et al.* (2008) does not work any more. Strict liability is thus preferable to negligence because only low levels of standard of prevention can be adopted under negligence (because of a low R&D level, leading to a few efficient technology); this rule thus leading to low levels of R&D and risk prevention measures.

5 Discussion and conclusion

In this paper, we suggest a model of innovation and diffusion of a new technology among firms, engaged in risky activities, who have different abilities regarding R&D: one innovative firm faces one non-innovative firm, but the latter has the possibility to imperfectly imitate the innovation once developed (output spillovers). We consider a "double-impact" innovation, in the sense that the technological progress it provides has both an impact on the cost of applying risk prevention measures, *and* an impact on the probability of accident. The aim of this study, in the spirit of Endres *et al.* (2008), is to compare two liability rules (strict liability and negligence) in terms of incentives to prevent a risk of accident and to engage in R&D to design a new risk prevention technology that is more efficient.

Two key facts have to be highlighted. First we find, in our context, a result which is similar to those of Endres *et al.* (2008): in the presence of an innovation which only impacts the cost of prevention and in the presence of spillovers (leading to suboptimal incentives to R&D), the negligence rule may be preferable to strict liability. Indeed, under perfect information, the Regulator knows the whole set of technological possibilities. He can act as a leader (in the sense of Stackelberg) by fixing a standard of prevention, regardless of the innovative firm's decision in terms of R&D, in order to have an influence on this decision. By fixing a standard of prevention beyond the level of prevention that would prevail under strict liability, the Regulator provides more incentives to invest in R&D in order to reduce the cost of complying with the standard of prevention. This mechanism partially offsets the suboptimal incentives to invest in R&D (related to the presence of spillovers), and thus leads to a decrease in the social cost of activity. However, when the technological progress sufficiently impacts the probability of accident, our study shows that strict liability is socially preferable to negligence; in the limit case where the innovation is strictly a "safety-innovation" the negligence rule provides no incentives to innovate or to adopt the new technology.

Hence, these results extend the result of Endres *et al.* (2008) to a different context, with diffusion of the innovation, but they also restrict it since the *nature* of the innovation plays a key role on the ranking of liability rules in terms of incentives to innovate (in order to reduce the risk).

Nevertheless, the economic analysis of externalities (risk, pollution) prevention *via* technological change induced by the legal frame is relatively new. So this study could (and should) be extended, and some strong assumptions have to be relaxed.

First of all it would be desirable, in a first extension, to take into account the possibility for the firms to be insolvent in the case of an accident, especially in the frame of a limited liability regime. In this study, we have put aside this possibility in order to lighten calculations and to easily compare our results with those of Endres *et al.* (2008). However, in the presence of a limited liability regime, it is well-known in the economic analysis of civil liability that strict liability may induce, for a given technology, suboptimal behaviors in terms of risk prevention when the potential damage are higher than the patrimonial value of the firm. In this regard, a negligence rule may be preferred to the extent it provides incentives to adopt a higher level of prevention measures than strict liability, thanks to the possibility for the firm to be exempted from liability in the case of an accident (see Shavell (1986)). However we show that, in the presence of a double-impact innovation, strict liability may induce higher efforts in R&D when the safety-impact of the innovation is sufficiently important. As a consequence, in the presence of a limited liability regime and high potentiel damage, a trade-off may appear in some contexts: for a given technology the negligence rule induces more risk prevention measures, but strict liability permits to induce more innovation, leading to a more efficient risk prevention technology. Moreover, in the presence of a *stochastic* R&D process (that does not succeed with certainty), the benefits from applying a negligence rule may be higher: to obtain a higher level of risk prevention measures with certainty may be more valuable than obtain a higher investment in R&D leading, *without* certainty, to a more efficient risk prevention technology.

Then, we have to temper the scope of our results in the light of the assumptions we pose. Indeed we suppose perfect information, notably between the Regulator, the Court and the firms. But in the presence of imperfect information between these actors, applying a negligence rule may be problematic in two respects. On the one hand, applying such a rule needs to collect information to define *ex ante* the standard of prevention. Beyond the cost of such a collect, an inaccurate definition of the standard provides suboptimal incentives to prevent the risk. On the other hand, information have also to be collected *ex post* to establish the liability of the firms in the case of accidents. Beyond the direct cost of gathering information, other costs have to be taken into account: when the Court imperfectly observes the firms' behaviors in terms of risk prevention, an uncertainty is introduced in the sense that the firms do not know with certainty what level of risk prevention measures to adopt in order to be exempted from liability. This may provide suboptimal incentives to prevent the risk, and it can lead to judicial error in the establishment of liability (see e.g. Fluet (2010)). All these costs, that we do not take into account in our analysis, suggest that the efficiency of the negligence rule may be overestimated when perfect information is supposed.

Finally, we have to keep in mind that applying a negligence rule also question the allocation of the costs of the damage. Indeed, when the firms comply with the standard of prevention, all the cost of the damage is borne by the victims. In the presence of large-scale damage, such a situation may be socially very costly. Even if the negligence rule can provide more incentives to innovate and to prevent the risk (in the presence of an innovation that mainly impacts the cost of risk prevention - low impact on the probability of accident), thus permitting to reduce the probability of occurrence of an accident, to allocate all the cost of the accident to the victims necessarily raises the question, for the Society, of the trade-off between equity and prevention.

Appendix

Proof of Proposition 2

Point (ii): whatever the liability rule that is applied, at equilibrium we have $x_i^k = x_i^*$ (e given, $k = SL, N$) and we have innovation *and* diffusion, or no innovation: $\forall\ \alpha < 1$, there is no situation where I has an interest to innovate and NI has no interest to adopt the new technology. Hence, the social cost can be written as ($\forall e > 0$)

$$SC = 2[c_B(x_B^*, e) + p_B(x_B^*, e)D] + e \tag{16}$$

If, $\forall e$ such that $e < e^*$, an increase in e is socially desirable, then point (ii) is demonstrated. We have:

$$\frac{dSC}{de}|_{0<e<e^*} = $$
$$2\frac{\partial c_B(x_B^*, e)}{\partial e} + 2\frac{\partial p_B(x_B^*, e)}{\partial e}D + 1 + 2\frac{dx_B^*}{de}.\frac{\partial c_B(x_B^*, e)}{\partial x} + 2\frac{dx_B^*}{de}.\frac{\partial p_B(x_B^*, e)}{\partial x}D \tag{17}$$

$$\Leftrightarrow \underbrace{2\frac{\partial c_B(x_B^*, e)}{\partial e} + 2\frac{\partial p_B(x_B^*, e)}{\partial e}D + 1}_{<0} + 2\frac{dx_B^*}{de}.\underbrace{\frac{\partial c_B(x_B^*, e)}{\partial x}}_{V:>0} + 2\frac{dx_B^*}{de}.\underbrace{\frac{\partial p_B(x_B^*, e)}{\partial x}D}_{Z:<0}$$

About the negativity of the first expression with a brace, see eq. (7) and consider $e < e^*$ and $\frac{\partial^2 p_B(x,e)}{\partial e^2} > 0$, $\frac{\partial^2 c_B(x,e)}{\partial e^2} > 0$. Concerning the expressions V and Z, we can check that Z is, in absolute value, higher than V by considering (4) and knowing $\frac{\partial^2 p_B(x,e)}{\partial x \partial e} < 0$ and $\frac{\partial^2 c_B(x,e)}{\partial x \partial e} < 0$. Moreover, this property permit to check than $\frac{dx}{de} > 0$ (or we can use the implicit functions theorem: $\frac{dx}{de} = -\frac{\frac{\partial^2 c_B(.,.)}{\partial x \partial e}}{\frac{\partial^2 c_B(.,.)}{\partial x^2}} > 0$). All these elements lead to $\frac{dSC}{de}|_{0<e<e^*} < 0$.

♦

Proof of Proposition 3

This proof follows three points (detailed in the article). Point 1/: from the proof of point (ii) of the Proposition 2, we know that, for a given $e > 0$, the social cost of activity is the same whatever the liability rule in force. $\forall e$ with $e < e^*$, an increase in e reduces the social cost of activity. Given $e^{SL} < e^*$ when $\alpha > 0$, an increase in e beyond the level e^{SL} is socially desirable.

Point 2/: admit that the Regulator applies a standard $\bar{x}_B = x_B^{**}$ (which is the level of prevention that would be adopted under strict liability in the absence of spillovers). We obtain:

e^N such that: $-(2-\alpha)\frac{\partial c_B(x_B^{**},e^N)}{\partial e} = 1$, and e^* such that: $-2\frac{\partial c_B(x_B^{**},e^*)}{\partial e} - 2\frac{\partial p_B(x_B^{**},e^*)}{\partial e}D = 1$

We have $e^N < e^*$ (spillovers and externalization of the social benefit in terms of reduction in expected damage).

Now we have to compare e^N to e^{SL}. First, considering (4) with $e = e^*$ then with $e = e^{SL}$ (knowing $\frac{\partial^2 p_B(x,e)}{\partial x \partial e} < 0$), we obtain $x_B^{**} > x_B^{SL}$. Knowing $\frac{\partial^2 c_B(x,e)}{\partial x \partial e} = \frac{\partial^2 c_B(x,e)}{\partial e \partial x} < 0$ it follows:

$-(2-\alpha)\frac{\partial c_B(x_B^{**},e^{SL})}{\partial e} > -(2-\alpha)\frac{\partial c_B(x_B^{SL},e^{SL})}{\partial e}$

But at equilibrium we have (respectively under negligence and under strict liability):

$-(2-\alpha)\frac{\partial c_B(x_B^{**},e^N)}{\partial e} = 1$, and $-(2-\alpha)\frac{\partial c_B(x_B^{SL},e^{SL})}{\partial e} - (2-\alpha)\frac{\partial p_B(x_B^{SL},e^{SL})}{\partial e}D = 1$

For $\frac{\partial p_B(.,e)}{\partial e} = 0$ we obtain:

$-(2-\alpha)\frac{\partial c_B(x_B^{**},e^{SL})}{\partial e} > -(2-\alpha)\frac{\partial c_B(x_B^{**},e^N)}{\partial e} = -(2-\alpha)\frac{\partial c_B(x_B^{SL},e^{SL})}{\partial e} = 1$

Hence, when $|\frac{\partial p_B(.,e)}{\partial e}|$ is sufficiently low (innovation that mainly impact the cost of prevention), and knowing $\frac{\partial^2 c_B(x,e)}{\partial e^2} > 0$ we obtain $e^* > e^N > e^{SL}$.

However, if the importance of $|\frac{\partial p_B(.,e)}{\partial e}|$ comparatively to $|\frac{\partial c_B(.,e)}{\partial e}|$ is sufficiently high, the marginal benefit from R&D under strict liability can be deeply higher than the marginal benefit under negligence (for a given x). Knowing $\frac{dx}{de} > 0$, in the presence Regulator acting as a follower we can obtain: $e^{SL} > e^N$ and $x_B^{SL} > \bar{x}_B$. This difference becomes stronger with the relative weight of $|\frac{\partial p_B(.,e)}{\partial e}|$: beyond some threshold, the importance of the safety-impact is so high that it is impossible for a firm to adopt a standard of prevention the level of which is higher than the level of prevention that would prevail under strict liability: the level of x_B^{SL} is too high, too costly to reach (knowing the degree of technological advancement that can be reached under negligence - relatively low incentives to R&D under negligence in that case). As a result, it is possible to impose a standard of prevention $\bar{x}_B > x_B^{SL}$ only if the safety-impact ($|\frac{\partial p_B(.,e)}{\partial e}|$) of the innovation is limited.

Point 3/: We have: $SC = 2[c_B(\bar{x}_B, e^N) + p_B(\bar{x}_B, e^N)D] + e^N$ Then:

$$\frac{dSC}{dx} = 2\frac{\partial c_B(\bar{x}_B, e^N)}{\partial x} + 2\frac{\partial p_B(\bar{x}_B, e^N)}{\partial x}D + \frac{de^N}{dx} + 2\frac{de^N}{dx}.\frac{\partial c_B(\bar{x}_B, e^N)}{\partial e} + 2\frac{de^N}{dx}.\frac{\partial p_B(\bar{x}_B, e^N)}{\partial e}D$$

$$\Leftrightarrow \underbrace{2\left[\frac{\partial c_B(\bar{x}_B, e^N)}{\partial x} + \frac{\partial p_B(\bar{x}_B, e^N)}{\partial x}D\right]}_{(V)} + \frac{de^N}{dx}\underbrace{\left[1 + 2\frac{\partial c_B(\bar{x}_B, e^N)}{\partial e} + 2\frac{\partial p_B(\bar{x}_B, e^N)}{\partial e}D\right]}_{(Z)}$$

(V) represents the net marginal social benefit from prevention, (Z) represents the net marginal social benefit from R&D.

If we pose $\bar{x}_B = x_B^{SL}$, we obtain:

$$\underbrace{-2\left[\frac{\partial c_B(x_B^{SL}, e^N)}{\partial x} + \frac{\partial p_B(x_B^{SL}, e^N)}{\partial x}D\right]}_{V:=0} + \frac{de^N|_{\bar{x}_B = x_B^{SL}}}{dx}\underbrace{\left[1 + 2\frac{\partial c_B(x_B^{SL}, e^N)}{\partial e} + 2\frac{\partial p_B(x_B^{SL}, e^N)}{\partial e}D\right]}_{Z:<0}$$

The condition (V) is equal to zero (equilibrium condition of x_B^*) while condition (Z) is negative (see (15)). As a consequence, the negativity of $\frac{dSC}{dx}|_{\bar{x}_B = x_B^{SL}}$ is verified from the moment that: $\frac{de^N|_{\bar{x}_B = x_B^{SL}}}{dx} > 0$. By using implicit functions theorem we obtain: $\frac{de}{dx} = -\frac{\frac{\partial^2 c_B(x,e)}{\partial x \partial e}}{\frac{\partial^2 c_B(x,e)}{\partial e \partial e}} > 0$. ♦

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