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about limited liability?** »

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Large-scale risks and technological change: What about limited liability?[*]

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Abstract

We consider a firm that has to choose a technology to produce a given good. This technology drives a multiplicative large-scale risk of incident for Society: the total potential level of damage increases with the level of activity. Contrary to what is often argued in the literature, we show that limited liability can be more incentive for technical change than an unlimited liability rule, depending on the magnitude of the technological change and on the firm's size. In a second part of the paper, taxes are introduced. We show how manipulating the tax rate with respect to the technological choice made by the firm still enlarges the set of parameters that lead to technological change under a limited liability rule. Our normative results provide some arguments in favor of the limited liability rule, often considered as the main explanation of partial large-scale risk internalization by firms.

Keywords: Technological risk, limited liability, incentives, technical choice, taxes.

JEL Classification: D81, H23, K39, Q55.

1 Introduction

Limiting the losses of a firm in the case of bankruptcy to her net value permits her to innovate and to levy funds for research and development in some rather reassuring economic and legal context. Since innovation is a key factor of the economic growth, the limited liability rule seems to be a good legal rule in the light of only these arguments. Nevertheless, it is common knowledge, since Shavell (1986)'s work in particular, that a limited liability rule may also induce either partial risk internalization by firm or over-investment in risky activities. Having to pay only up to the net value of their assets in the case of an incident, some firms and their shareholders may have some interest to conduct some projects that have a negative net present value when taking into account all the technological risk that is tranferred to Society. In order to countervail these negative effects, some papers focus on the usefulness of a rule that would extend the financial liability to the partners of a responsible firm. This partner (a bank for instance) will have to pay for extra damages if the firm is bankrupted and cannot pay up to a certain amount (see Klimek, 1990, for some practical cases involving US banks in the eighteens). Such a rule should increase the available funds for compensation. But it may also lessen the incentives of firms to invest in prevention, for their financial responsibility is moved towards the other operators (Beard, 1990; Pitchford, 1995 ; Boyd and Ingberman, 1997; Boyer and Laffont, 1997; Dionne and Spaeter, 2003; Hiriart and Martimort, 2006). This last literature assumes that technological choice is exogenous to the decision process of the firm. Thus it does not allow it to consider the role that technological change could play in the technological risk management. Incentives driven by technological change are not considered despite the fact that firms are, in practice, willing to engage in such a process.

Technological change in the framework of pollution control is considered by Milliman and Prince (1989). Concerning R&D programs, some analyses take into account the imitation abilities of firms that compete on a given market (Fischer et al., 2003; Parry, 1995), the trade-off between a more productive technology, at given emissions, and a less pollutant one (Magat 1978, 1979), while others focus on the technological

choice of firms within the framework of imperfect competition (*à la Bertrand*) (Requate, 1998). These analyses take the liability context as given, ignoring the contributions of the economic analysis of liability. The agent is considered as always financially solvent whatever the state of nature that occurs, and she makes her choices in an unlimited liability context. If unlimited liability is proned by some economists and some jurists from a normative point of view (Faure, 1995; Hansmann and Kraakman, 1991; Halpern, Trebilcock and Turnbull, 1980), it is much more complicate to implement it in practice. Indeed Alexander (1992, p. 389) writes "To the extent that the proposal could constitutionally be implemented, enforcement would raise substantial procedural obstacles". For some practical reasons, the law could even be unenforceable (think about out-of-state shareholders would should be identified) and implementation costs can be higher than the net benefit for Society[1]. In the particular case of large-scale (or catastrophic) risks (Schmitt and Spaeter, 2007, for nuclear risks for instance), the efficiency of unlimited liability in terms of risk internalization can still be put in doubt. Desasters following a dramatic technological accident can be so high that no firm and no operator of her, even if well identified, is able to pay for compensation and restoration. Thus the liability can be as unlimited as possible, victims will never be fully indemnified. Even so, it can take a very long time until a legal court obtains all the information and takes a decision about who should pay and how much.[2]

In this paper, we show that limited liability does not always lead to less risk-internalization or poorer incentives to change for a safer technology. Moreover, taxes can still improve the incentives driven by limited liability. Our analysis is conducted in two stages. First, we focus on the incentives that unlimited and limited liability make emerge in terms of technological change[3]. The first rule implies that the potential injurer (the firm and her shareholders) will always have to pay for all the damage caused by her

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[1]See also Easterbrook and Fischel (1985), and Grundfest (1992).

[2]In a rather different framework and by considering, in particular that safety investments can impact the level of damage per unit of production, Boyd and Ingberman (1994) also provide some arguments in favor of capped damages.

[3]Contrary to Magat (1978, 1979) and Fischer et al. (2003), we do not consider technologicall innovation. The firm chooses between two existing technologies, an "old" technology and a new one (just arrived on the market).

activity. Thus her profit may be negative. The second rule limits the *ex post* liability of the firm for she will have to pay for damages only up to her present net value. Her lowest possible profit equals zero and it corresponds to bankruptcy state. In such a situation, which may occur after a huge incident, the firm and her shareholders will not have to compensate victims out of their pocket. In a second part of the paper, we associate taxes with a limited liability rule in order to enlarge the set of parameters for which a firm is willing to move from a default technology to a safer one.

One originality of our simple model deals with this combination of rules and taxes. Even if, in practice, it is common use, such a setting has never been analyzed from a normative point of view. One can learn about the behaviors it yields in practice, for instance by observing strategies within the industries, but one does not know how it can help getting closer to socially optimal behaviors in terms of technological change and of activity levels. Second, considering that the risk driven by the activity of the firm is simultaneously affected by the technological choice and the level of production is also an important point of our analysis. Many models relative to large-scale risk management in the literature assume that the risk of incident is affected by some investment in prevention (which could be, in a certain manner, compared to "small" technological change) but not by production. In our setting, a technological change induces also a change in the marginal cost of production and the optimal level of activity becomes a best response to the optimal technological choice. It is important to notice that a safer technology leads to a higher production costs reflecting the past R&D process that permitted to develop this new technology. This is rather different from the literature focusing on technologies that lead to a reduction of the abatement costs of some pollution. Moreover, taxes conditioned by the adopted technology are considered in the last section. This would not be possible if technological change were only resumed by a change in the incident probability. Thus our setting is more general than just assuming, for a given level of activity, a decrease of the probability of incident obtained thanks to some efforts done by the firm. Shavell (1980, 2004) also considers that the damage is affected by the level of activity, but recall that he considers the negligence rule, while we focus on limited liability.

A last important point of our model is that, by choosing *ex ante* her level of activity, a limited liability firm also chooses to benefit or not to benefit *ex post* from what we call in the paper the '*ex post* legal financial protection'. In other terms, if she chooses a level of activity that pushes her into bankruptcy after an incident, she will be liquidated but she will not have to pay more than the net value of her assets. If, on the contrary, she adopts a level of activity lower than the bankruptcy level, then her profit will always be positive, bankruptcy will never occur, all risk will be internalized by the firm and *ex post* legal financial protection will never be mobilized.

Several main results can be depicted here. We show that limited liability can be more incentive in terms of technological change than an unlimited liability rule when the level of technological damage depends on the level of activity. In particular, for large technological risks (high levels of damage in the case of an accident), high-capitalized firms may have more incentives for technological change under a limited liability.

Nevertheless, it must be noticed that the safest technology is not always the 'ideal' one for Society for it can push the firm to increase her level of activity and, therefore, it contributes to higher damage in the case of an accident. The possibility of manipulating the rate of tax with respect to the technological choice made by the firm permits it to mitigate this negative effect due to production in excess. This is still showed in the model of Section 3 which combines taxes with a limited liability rule.

The paper is organized as follows. Section 2 presents the basic hypotheses and the analysis on unlimited and limited liability. Section 3 focuses on the mix policy (taxes and rules). Section 4 concludes the paper.

2 Liability rules and technological choice

In this section, we analyze the technological choice made by a risk-neutral firm facing a technological risk and the level of activity she decides to adopt when she is subject first to unlimited liability, then to limited liability.

Consider a competitive economy with a representative risk-neutral firm selling an

homogeneous product at a price p. The demand displays an infinite elasticity. The firm's activity induces a major risk of incident, which occurrence probability depends on the type of production technology she adopts. The firm has to choose between two technologies indexed by $i = 1, 2$. The first one is the technology initially adopted by the firm (default technology). It is less costly than the second one, but it also drives a higher incident probability. We denote it φ_i, with $\varphi_i \in [0, 1]$ and $\varphi_2 < \varphi_1$. We still denote y_i the level of production chosen by the firm when she uses technology i ($i = 1, 2$). The production cost for technology i equals $Z_i y_i^2$ with $Z_1 < Z_2$.

Let d be the damage rate, that is the level of damage per unit of production borne by Society. Hence the total amount of damage dy_i following an accident depends on the level of activity y_i and, as a direct consequence, on the technological choice. The random variable defining the risk of accident for technology i can be denoted as $\widetilde{D_i} \equiv (1 - \varphi_i, \varphi_i; 0, dy_i)$.

Finally, assume that the firm finances her activity out of her equity E, with $E > 0$.

Perfect information about the decisions of the firm takes place in this paper. The firm chooses the level of her activity and the technology she decides to keep (if $i = 1$) or to adopt (if $i = 2$). Thus the level of activity y_i that maximizes her expected profit is a best response to a technology i.

2.1 Unlimited versus limited liability

Under an unlimited liability rule, a firm has to pay *ex post* for any damage caused by her activity, whatever her level of activity. In such a setting, *ex post* profits can be negative and the entire risk of incident is internalized. If the amount of damages is higher than the net value of the firm at the time of the accident, owners will have to pay out of their pocket. Formally, the firm's maximization program is:

$$\max_{y_i, i} E\left(\widetilde{\Pi_i}\right) = py_i - Z_i y_i^2 - \varphi_i dy_i + E \tag{1}$$

The private level of activity that is solution to (1), and denoted y_i^{UL}, satisfies:

$$y_i^{UL} = \frac{p - \varphi_i d}{2Z_i}, \quad i = 1, 2 \tag{2}$$

Knowing that the firm owns the technology 1, she decides to adopt the safer technology 2 if $E[\widetilde{\Pi_2}] - E[\widetilde{\Pi_1}] > 0$. After computation and arrangement, we obtain the results in Proposition 1 hereafter.

Proposition 1 *Under the unlimited liability rule, a risk-neutral firm chooses technology 2 if and only if :*

$$\frac{(p - \varphi_1 d)^2}{Z_1} < \frac{(p - \varphi_2 d)^2}{Z_2} \tag{3}$$

Proof. See the appendix. ◆

Inequality (3) is a standard difference of net marginal profits evaluated at optimum (the level of activity for each technology is the one that maximizes the expected profits). Technological change occurs if doing so is profitable.

Now let us consider the case in which the firm is protected by a limited liability rule. This means that she is, *ex ante*, responsible for all the damage caused by her activity but, *ex post*, she will not have to pay more than her net present value. Hence, if the damage is higher than the firm's net value, part of it will be borne by Society. Contrary to what is done in Beard (1990), Pitchford (1995) and Dionne and Spaeter (2003), who also consider limited liability, our approach endogenizes both the level of damage observed in the case of an accident and the possibility for the firm to effectively benefit, or not, from the financial limitation *ex post.* To well understand these features, we need to define the level of activity that pushes the firm into bankruptcy following an incident.

Lemma 1 *Let $\widehat{y_i}$ be the production level that induces an ex post profit equal to zero when technology i (i = 1, 2) is chosen and an accident occurs. We have:*

$$\widehat{y_i} = \frac{(p - d) + \sqrt{(p - d)^2 + 4Z_i E}}{2Z_i} \tag{4}$$

Proof. By definition of $\widehat{y}_i$, the after accident profit writes:

$$p\widehat{y}_i - Z_i\widehat{y}_i^2 - d\widehat{y}_i + E \;=\; 0$$
$$-Z_i\widehat{y}_i^2 + (p - d)\widehat{y}_i + E \;=\; 0$$

Both roots are

$$\widehat{y}_i = \frac{(p - d) + \sqrt{(p - d)^2 + 4Z_iE}}{2Z_i} \text{ and } \widehat{y}_i = \frac{(p - d) - \sqrt{(p - d)^2 + 4Z_iE}}{2Z_i}$$

The second root being always negative, Lemma 1 is proved. ◆

In this framework, if a firm protected by the limited liability rule adopts a level of activity y_i higher than $\widehat{y}_i$, she will benefit from the legal financial protection beyond her net value in the case of an accident: she will be declared as bankrupted and all her assets will be confiscated for compensation, but not more. Her final after accident profit will be zero whatever her activity level y_i with $y_i \geq \widehat{y}_i$. If the firm chooses y_i such that $y_i < \widehat{y}_i$, her profit will always be positive even in the case of an accident. The firm will always be able to pay for all the damages and she will not be in the situation of needing the legal protection offered by the limited liability rule. In this last situation, we will say that she has decided, by choosing a level of activity lower than the bankruptcy threshold $\widehat{y}_i$, not to be protected by *ex post* limited liability and to internalize all the risk driven by her activity.

As a direct consequence, the decision of taking or not taking advantage of the limited liability rule becomes endogenous to the model. This modifies the firm's maximization program compared to the preceding case (with unlimited liability). Now, it is composed of two steps. First, the firm acts as if she would be under an unlimited liability rule and she decides the optimal level of activity in this framework. Second, if the level of activity she chooses in the first step is higher than $\widehat{y}_i$, then she considers again her maximization program but in the limited liability frame. If the activity level is lower than $\widehat{y}_i$, the firm considers her decision process as taking place in an environment identical to the one that prevails with unlimited liability, with $y_i \in [0, \widehat{y}_i]$. Nevertheless, by doing so she will never be concerned by bankruptcy considerations even in the case of an accident, contrary to

the unlimited liability case.

If the firm chooses $y_i > \widehat{y_i}$ (that means that $E\left[\Pi(y_i)\right] > E\left[\Pi(y_i^0)\right]$, $\forall y_i^0 \leq \widehat{y_i}$), she will benefit from *ex post* legal protection in the case of an accident. Her new program becomes:

$$\max_{y_i}(1 - \varphi_i)\left[py_i - Z_i y_i^2 + E\right] \qquad (5)$$

In the course of the paper, we will denote by y_i^{LL+} the optimal level of activity when the firm chooses to benefit from *ex post* legal protection with technology i (i.e. $y_i^{LL+} > \widehat{y_i}$) and by y_i^{LL-} the optimal level of activity in the other limited liability case (i.e. $y_i^{LL-} < \widehat{y_i}$).

The optimal level of activity y_i^{LL+}, solution to Program (5), satisfies:

$$y_i^{LL+} = \frac{p}{2Z_i} \qquad (6)$$

On the contrary, if the firm chooses to produce less than $\widehat{y_i}$, her optimization program is similar to (1) and we obtain again

$$y_i^{LL-} = \frac{p - \varphi_i d}{2Z_i}. \qquad (7)$$

The difference is that profits will never be negative since $y_i^{LL-} < \widehat{y_i}$, contrary to what can be obtained in the unlimited liability model.

Now, let us ask whether a technological change also induces a change in the willingness of the firm to adopt or to give up *ex post* legal protection.

Proposition 2 *Consider a risk-neutral firm who benefits from ex post legal protection with technology 1 ($y_1^{LL+} > \widehat{y_1}$) and who decides to adopt technology 2.*

This firm turns to full risk internalization after technological change ($y_2^{LL-} < \widehat{y_2}$) if and only if

$$\varphi_1 - a \leq \varphi_2 < \varphi_1, \qquad (8)$$

with $a = \frac{4E}{d^2}(Z_2 - Z_1)$.

In other (non technical) words, full internalization after technological change holds particularly for incremental innovation.

Proof. See Appendix. ♦

Incremental innovation means that technology 2 provides a small improvement in the safeness compared to technology 1: the difference between φ_1 and φ_2 should not be too high.

Another important point is that Condition (8) can never be satisfied for $E = 0$. And the more E, the more the chance to observe full internalization of the risk after a technological change. As a direct consequence, high-capitalized firms seem to be more concerned by the result of Proposition 2. This is rather intuitive since high capitalized firms have more equity that can be confiscated for compensation following an incident.

In the following Proposition 3, we consider the opposite case to Proposition 2 and we stress the conditions that lead to the choice of ex post legal protection after technological change by the firm.

Proposition 3 *Consider a risk-neutral firm that fully internalizes the risk of incident with technology 1 ($y_1^{LL-} < \widehat{y_1}$) and that chooses to adopt technology 2.*

(i) This firm turns to partial risk internalization ($y_2^{LL+} > \widehat{y_2}$) if and only if

$$\varphi_2 < 1 - b < 1 - c \leq \varphi_1, \tag{9}$$

with $b = \frac{(p-d)^2 + 4Z_2 E}{d^2} \geq 0$ and $c = \frac{(p-d)^2 + 4Z_1 E}{d^2} \geq 0$.

(ii) In other (non technical) words, partial risk internalization after a technological change holds particularly for radical innovation.

Proof. See Appendix. ♦

Radical innovation means that technology 2 provides a high improvement in the safeness compared to technology 1: φ_2 should be significantly lower than φ_1. Furthermore, still notice that Condition (9) is always satisfied for $E = 0$. Thus small firms seem to have more incentives than high-capitalized ones to choose ex post legal protection after a technological change. It was also the case for incremental innovation since they move less often to full internalization (see Proposition 2).This can be explained by the fact

that the level of activity that may push high-capitalized firms into bankprutcy after an accident is higher than for small firms knowing that the equity E of the former is higher.

Radical innovation can induce more future uncertainty for the firm. Deciding to be financially protected *ex post* in the case of an incident can be considered as a way to deal with this increasing uncertainty. Nevertheless, this uncertainty is not explicitly captured by our model. Moreover, the firm is risk neutral. Here the optimality of ex post financial protection is a direct consequence of the increase of the level of activity: the good becoming more profitable, the firms decides to increase her production such that the total damage, in the case of an incident, leads to bankruptcy.

The incentives to benefit or not from *ex post* legal protection being identified, we still have to analyze the conditions under which technological change really occurs under limited liability. Since the maximization program is non differentiable in $\widehat{y_i}$, we have to consider the successive four following cases:

a) Technology 1 and full internalization => technology 2 and full internalization.

b) Technology 1 and partial internalization => technology 2 and full internalization.

c) Technology 1 and partial internalization => technology 2 and partial internalization.

d) Technology 1 and full internalization => technology 2 and partial internalization.

In each case we must compare the adequate expected profits. Nevertheless, being interested by arguments that could help a decisionmaker in defining incentives for both technological change and full internalization, we focus essentially on cases a) and b). Cases c) and d) are proposed in the Annex.

For the sake of clarity, we keep referring to full internalization when talking about limited liability without *ex post* protection ($y_i^{LL-} < \widehat{y_i}$) and to partial internalization when the firm chooses *ex post* legal protection ($y_i^{LL+} \geq \widehat{y_i}$).

Proposition 4 *Assume that a limited liability rule holds.*

a) A firm having adopted full risk internalization with technology 1 turns to technology 2 while keeping full risk internalization if:

$$\frac{(p - \varphi_1 d)^2}{Z_1} < \frac{(p - \varphi_2 d)^2}{Z_2} \tag{10}$$

or

$$0 < (p - \varphi_2 d)y_2^{LL-} - (p - \varphi_1 d)y_1^{LL-} \tag{11}$$

b) A firm having adopted partial risk internalization with technology 1 turns to technology 2 and full risk internalization if:

$$p(1 - \varphi_1)y_1^{LL+} - (p - \varphi_2 d)y_2^{LL-} < 2\varphi_1 E \tag{12}$$

Proof. See Appendix. ♦

Each inequality in Proposition 4 can be interpreted in terms of expected marginal cost and marginal benefit following a technological change.

This ends the separate analysis of both liability rules. We must know compare them in terms of incentives to technological change.

2.2   More incentives with a limited liability rule

In this section, we highlight the conditions under which a firm has more incentives to move from technology 1 to technology 2 when she is protected by limited liability.

Recall that a firm who decides *ex ante* to give up the *ex post* legal protection (by choosing $y_i^{LL-} < \widehat{y}_i$) has a maximization program close to the one obtained in an unlimited liability rule. We do not consider the case here. We focus on the more striking case relative to the comparison between unlimited liability and limited liability with legal protection.

Proposition 5 *Denote as 'LL rule' the limited liability rule with ex post legal protection and as 'UL rule' the unlimited liability rule.*

(i) $2d - p > 0$ is a necessary condition for a firm to choose a LL rule.

(ii) The firm under a LL rule will move more frequently from technology 1 to technology 2 than with a UL rule iff:

$$(\varphi_1 - \varphi_2)4E > d^2(\frac{\varphi_2^2}{Z_2} - \frac{\varphi_1^2}{Z_1}) - p(2d - p)(\frac{\varphi_2}{Z_2} - \frac{\varphi_1}{Z_1}) \tag{13}$$

(iii) Point (ii) is all the more satisfied since E is high.

Proof. See the appendix. ♦

Point (i) implies that limited liability with *ex post* legal protection becomes attractive for firms only for some large risks: d must be sufficiently large compared to p.[4]

Point (ii) provides conditions under which a limited liability rule (with *ex post* legal protection) is more incentive in terms of technological change than the unlimited liability rule. This result is interesting since it implies that firms may prefer a technology that costs more with certainty, while limited liability permits them to be financially (partially) protected in the case of a huge incident. Recall that when changing their technology, they also change their level of activity and, as a direct consequence of our model, all the parameters of their profits (gross returns, total production costs and expected damages). Here technological change leads simultaneously to risk mitigation and change in the production supply.

Finally, limited liability seems to be a good way to simultaneously incite firms to go on some markets (to produce) and to choose safe technologies. Here, risk mitigation and limited liability are not opposed, contrary to what is often showed in the literature.[5]

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[4]Nevertheless, notice that if p is very small the damage rate does not need to be high. Actually, what is important is the total level of damage dy_i. And if the firm sells a good with a small price p, she will, generally, also produce a large quantity y_i of this good in order to make profitable the purchase of the technology. Thus, the technological risks that we consider are large because d or y_i are high.

[5]Recall that Shavell (1986), Beard (1990), Pitchford (1995), Boyer and Laffont (1997), and Dionne and Spaeter (2003) show, among other points, that limited liability of firms lead to less risk internalization and less prevention. These results have been obtained in models with levels of damage that do not depend on the level of activity of the firm. Moreover, less risk internalization is also the main argument used by some jurists to put in doubt the efficiency of limited liability(see, e.g., Hansmann and Kraakman, 1991).

Point (iii) provides an interesting comparative static result for decision-making. High capitalized firms will move more frequently toward a safer technology under a limited liability rule with *ex post* legal protection. Hence Point (iii) could also be an argument in favor of a differentiation in the liability rules applied in the industries[6], depending on the size of the firms and/or the type of technological innovation (incremental or radical) that is in force when comparing technology 1 and technology 2 (see Propositions 2 and 3).

3   A '(limited liability) rule and tax' policy

In this section, we focus on a mix policy, that is a policy that allows for the simultaneous use of a limited liability rule and some more standard incentive tools, such as taxes. The aim of such a mix policy is to enlarge the set of parameters for which a given risk-neutral firm has an interest in switching from technology 1 to technology 2, without having to use the so discussed unlimited liability rule.

Let us assume that the production is taxed. The technology chosen by the firm is observable by the regulator so that the tax rate can be differentiated with respect to the technology. We denote it as t_i, $i = 1, 2$.

Such an hypothesis calls for an explanation. It can be disturbing to assume that production, rather than marginal cost, is taxed[7]. But recall that the level of activity y_i chosen by the firm affects the level of risk borne by Society. What will be important is the ability of the regulator to fix the level of tax rate with respect to the technology he wants to be adopted by the firm. Recall that the firm can also mitigate the risk for a given level of activity by choosing the safer technology. Furthermore, the tax rate can be negative, so that subsidies might also exist. Thus a firm who would like to escape from paying too much tax can either reduce her production or move to the less taxed

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[6]This point could be an argument to apply limited liability to sectors in which it is usual to observe some widely held firms, as advocated by Halpern, Trebilcock and Turnbull (1980).

[7]Actually, such type of taxation is more usual in environmental policies, the aim of which being clearly to reduce emission and to give some incentives to change the pollutant technologies. Concerning heating gases for instance, several countries (Switzerland, Sweden, Norway, Denmark, Finland, Germany, England; while France tried in 2009, but failed, to implement a "carbon tax") have already adopted taxes based on the production of some specific sectors or on the consumption of some specific goods.

technology. She can also adopt simultaneously both strategies.

Under an unlimited liability rule, the new maximization program becomes:

$$\max_{y_i,i} E\left(\widetilde{\Pi_i}\right) = py_i - t_i y_i - Z_i y_i^2 - \varphi_i dy_i + E \tag{14}$$

or

$$\max_{y_i,i} E\left(\widetilde{\Pi_i}\right) = p_i y_i - Z_i y_i^2 - \varphi_i dy_i + E,$$

with $p_i = p - t_i$. Introducing such a tax is such like differentiating prices with respect to the chosen technology. Nevertheless, in this setting goods keep continuing to be sold at price p: No aspect of consumers' willingness to pay for safe products is considered. This is out of the scope of this paper.

The private level of activity solution to (14), and denoted y_i^{tUL}, satisfies:

$$y_i^{tUL} = \frac{p - t_i - \varphi_i d}{2Z_i}, \quad i = 1, 2 \tag{15}$$

And we obtain the following result. "Technology i becomes relatively more attractive" means that there exists a larger set of parameters' values that leads to the choice of technology i at optimum.

Proposition 6

(i) Under an unlimited liability rule combined with a tax on production, a risk-neutral firm chooses technology 2 if and only if :

$$\frac{(p - t_1 - \varphi_1 d)^2}{Z_1} < \frac{(p - t_2 - \varphi_2 d)^2}{Z_2} \tag{16}$$

(ii) Technology i becomes relatively more attractive following an increase in the tax rate t_j, $j \neq i$, $i = 1, 2$, $j = 1, 2$.

(iii) If $y_i^{tUL} > y_j^{tUL}$, then technology i becomes relatively more attractive following an identical and simultaneous decrease in both tax rates t_1 and t_2.

Proof. See Appendix. ♦

Since both technologies are substitutable, the regulator has several means for influencing the adoption of technology 2. Indeed he can increase t_1, decrease t_2 or even decrease both tax rates in some contexts. All these strategies lead to a higher attractiveness of technology 2, but the revenue of the tax agency is different.

Now, let us turn to the limited liability rule. Other things being equal, introducing taxes on production lessens the level of activity that pushes the firm into bankruptcy following an accident. Thus it deteriorates the financial condition of the firm. Nevertheless, the firm can react to taxation by modifying her level of activity. And, as a direct consequence, the total amount of damage in the case of an accident is also lowered.

Such as in Lemma 1, the level $\widehat{y_i^t}$ of production that induces an *ex post* profit equal to zero when technology i $(i = 1, 2)$ is chosen and an accident occurs is defined as satisfying $(p - t_i)\,\widehat{y_i^t} - Z_i\widehat{y_i^t}^2 - d\widehat{y_i^t} + E = 0$. Still here, the firm can decide to benefit or not to benefit from the *ex post* legal protection by choosing *ex ante* an adequate level of activity.

Assume that the firm chooses $y_i^t > \widehat{y_i^t}$. Her new program becomes $Max_{y_i^t, i}\quad (1 - \varphi_i)\left((p - t_i)y_i^t - Z_iy_i^{t2} + E\right)$. And the optimal level of activity denoted as y_i^{tLL+} satisfies:

$$y_i^{tLL+} = \frac{p - t_i}{2Z_i} \tag{17}$$

On the contrary, if the firm chooses to produce less than $\widehat{y_i^t}$, her optimization program is similar to (14), with the difference that it is never negative under the limited liability rule. We have :

$$y_i^{tLL-} = \frac{p - t_i - \varphi_i d}{2Z_i}, \quad i = 1, 2 \tag{18}$$

Proposition 7 *Assume that a limited liability rule holds.*

(i) A risk-neutral firm chooses to benefit from the legal protection in the case of an accident if and only if:

$$\varphi_i < 1 - \frac{(p - t_i - d)^2 + 4Z_iE}{d^2} \tag{19}$$

(ii) For a given technology $i = 1, 2$, a decrease in the tax rate t_i decreases the attractivity of ex post legal protection for the firm.

Proof. See Appendix. ♦

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Less tax leads to better risk internalization under a limited liability rule when techno-
logical change is not considered. Hence, taxation can improve risk internalization despite
the limitation of the maximum amount of loss suffered by a limited liability firm in the
case of an accident.

In Proposition 8 hereafter we consider some technological change. Since our aim is to
show that limited liability does not always lead to the worst risk internalization and to
the poorest incentives to move to safer technologies, we focus essentially on technological
change followed by full internalization.

Proposition 8 *Assume that a limited liability rule holds and that a unit tax, depending
on the chosen technology, is applied to each unit of production.*

*(i) A firm having adopted full risk internalization with technology 1 turns more fre-
quently to technology 2 with full risk internalization than in a system without tax if
$t_1 > t_2$.*

*(ii) A firm having adopted partial risk internalization with technology 1 turns more
frequently to technology 2 and full risk internalization than in a liability system without
tax if*

$$\frac{t_1(2p - t_1)(1 - \varphi_1)}{t_2(2(p - \varphi_2 d) - t_2)} > \frac{Z_1}{Z_2}$$

*This condition is all the more satisfied since t_1 is high for a given t_2 (t_2 is low for a
given t_1).*

Proof. See Appendix. ♦

In situations where applying unlimited liability would be too costly for Society (in
terms of innovative projects that would not been concretized or of information seeking
for instance), limited liability can be a good rule if it is combined with taxes depending
on the technological choice made by the firms.

4   Conclusion

In this paper, we have considered a firm the activity of which drives a technological,
large-scale risk for Society. The main objective of this paper was to show that a limited

liability rule can also be technical change incentive when compared to an unlimited liability rule. The introduction of taxes in the last section permitted it to reinforce this result under some conditions.

The risk of technological incident is multiplicative in the sense that the magnitude of the potential damage increases with the level of production. Two technologies were available: the default technology displays a higher probability of accident than the safer one, but also a lower marginal cost of production. By considering the relationship between the technological risk, the technical choice and the level of activity, one originality of our contribution was to allow the firm to choose to potentially benefit or not from the legal financial protection offered by a limited liability rule when a damage occurs. More explicitely, she could choose a level of activity such that she was never bankrupted in the case of a damage. In this way, she fully internalizes the risk despite the fact that she could benefit from limited liability.

One general result that we obtained is that a limited liability rule does not always lead to less risk internalization. Indeed, firms can choose a level of activity such that the induced amount of damage is not too high in the case of an incident. Beside, we have also showed that R&D, which would lead to safer technologies by decreasing the rate of damage, can induce less risk internalization when the level of activity is simultanously increased.

We have also showed that a limited liability firm who decides to invest in the safest technology also adopts full risk internalization if this new technology differs from the default one thanks to an incremental innovation, while she prefers to be *ex post* protected by legal protection if radical innovation has taken place. This result seems counterintuitive. Nevertheless the conditions required to observe some full risk internalization concern high-capitalized firms. Moreover, innovation permits it to have access to safer technologies and, in our model, this impacts directly the optimal level of activity of the firm. Hence, a radical innovation is not necessarily socially desirable for it can increase the level of activity chosen by the firm and then increase the level of damage in the case of an incident. This highlights the trade-off to be made in some specific settings by the regulator between *ex ante* mitigation (less chance to observe an incident) and *ex post*

mitigation (less damage if an incident occurs).

In the last section of the paper, we tried to enlarge the set of the conditions that lead to technological change by giving the regulator an additional regulatory tool, namely taxation. The tax rate is applied to production (recall that it affects the level of damage), and it can be differentiated with respect to the chosen technology. In this setting, it was showed that technological change AND full risk internalization is likely to be observed in a system where production obtained with the default technology is taxed, while the safest technology is exempted from tax payment.

All these results permit us to conclude first that limited liability can initiate technological change without always deteriorating risk internalization by the firm. Second, liability rules combined with more classical regulatory tools like taxation give several interesting and powerful dimensions to the regulator's policy. Lastly, these dimensions should be used in particular to differentiate the policies thanks to the type of sector that is considered (high-capitalized firms, small or medium firms) and with respect to the innovation that is in force (incremental or radical). The dangerousness of the activity should also be an important feature of the regulation as already argued by Shavell (1986, 2004). Indeed limited liability may not be preferred if the potential damage is huge even if technological change seems to be more likely to be observed with legal protection.

Our model is based on simple assumptions and its scope could (and should) be extended. The first extension could be to study the impact of the existence of a not yet finalized technology, in the sense that additionnal R&D is needed to properly assess its risk. This could permit us to study the behaviors of firms facing rules that compel them to do additionnal R&D or tests before using a new technology. Another interesting extension of this work could be to consider an endogeneous level of capital by allowing firms to borrow funds from a bank, and thus studying their behavior concerning risk management (choice of the technology and the activity level) when they are endowed with external funds (such as debt for instance) and equity.

Appendix

Proof of Proposition 1

We have to compute $E\left(\widetilde{\Pi_2}\right) - E\left(\widetilde{\Pi_1}\right) > 0$ at optimum:

$$py_2^{UL} - Z_2(y_2^{UL})^2 - \varphi_2 dy_2^{UL} + E > py_1^{UL} - Z_1(y_1^{UL})^2 - \varphi_1 dy_1^{UL} + E$$

$$\Leftrightarrow p(y_2^{UL} - y_1^{UL}) - (Z_2(y_2^{UL})^2 - Z_1(y_1^{UL})^2) - d(\varphi_2 y_2^{UL} - \varphi_1 y_1^{UL}) > 0$$

Using (2), we must have:

$$p(\frac{p - \varphi_2 d}{2Z_2} - \frac{p - \varphi_1 d}{2Z_1}) - (\frac{(p - \varphi_2 d)^2}{4Z_2} - \frac{(p - \varphi_1 d)^2}{4Z_1}) - d(\frac{\varphi_2(p - \varphi_2 d)}{2Z_2} - \frac{\varphi_1(p - \varphi_1 d)}{2Z_1}) > 0$$

$$\Leftrightarrow p[Z_1(p - \varphi_2 d) - Z_2(p - \varphi_1 d)] - \frac{1}{2}[Z_1(p - \varphi_2 d)^2 - Z_2(p - \varphi_1 d)^2]$$

$$-d[Z_1\varphi_2(p - \varphi_2 d) - Z_2\varphi_1(p - \varphi_1 d)] > 0$$

$$\Leftrightarrow Z_1(p - \varphi_2 d)[p - \frac{1}{2}(p - \varphi_2 d) - d\varphi_2] - Z_2(p - \varphi_1 d)[p - \frac{1}{2}(p - \varphi_1 d) - d\varphi_1] > 0$$

$$\Leftrightarrow Z_1(p - \varphi_2 d)[\frac{1}{2}(p - \varphi_2 d)] - Z_2(p - \varphi_1 d)[\frac{1}{2}(p - \varphi_1 d)] > 0$$

$$\Leftrightarrow Z_1(p - \varphi_2 d)^2 > Z_2(p - \varphi_1 d)^2$$

$$\Leftrightarrow \frac{(p - \varphi_1 d)^2}{Z_1} < \frac{(p - \varphi_2 d)^2}{Z_2} \tag{20}$$

Proposition 1 is demonstrated. ♦

Proof of Proposition 2.

First, let us show that a risk-neutral firm chooses, under limited liability and with technology i, to benefit from full internalization in the case of an accident if and only if:

$$\varphi_i \geq 1 - \frac{(p - d)^2 + 4Z_i E}{d^2}, \tag{21}$$

with $\frac{(p-d)^2+4Z_iE}{d^2} < 1$. This is the case if $E\left[\pi(y_i^{LL-})\right] \geq E\left[\pi(y_i^{LL+})\right]$:

$$
\begin{aligned}
py_i^{LL-} - Z_i(y_i^{LL-})^2 - \varphi_i dy_i^{LL-} + E &\geq (1-\varphi_i)(py_i^{LL+} - Z_i(y_i^{LL+})^2 + E) \\
(p - Z_i y_i^{LL-} - \varphi_i d)y_i^{LL-} + E &\geq (1-\varphi_i)((p - Z_i y_i^{LL+})y_i^{LL+} + E) \\
\frac{(p - \varphi_i d)}{2}\frac{(p - \varphi_i d)}{2Z_i} + E &\geq (1-\varphi_i)(\frac{p}{2}\frac{p}{2Z_i} + E) \\
(p - \varphi_i d)^2 - (1-\varphi_i)p^2 + 4Z_i\varphi_i E &\geq 0 \\
\varphi_i(-2pd + \varphi_i d^2 + 4Z_i E + p^2) &\geq 0 \\
-2pd + \varphi_i d^2 + 4Z_i E + p^2 &\geq 0 \\
\varphi_i &\geq 1 - \frac{(p-d)^2 + 4Z_i E}{d^2}
\end{aligned}
$$

It is easy to check that $\frac{(p-d)^2+4Z_iE}{d^2} < 1$ when the optimum for the firm is $y_i^{LL+} > \widehat{y}_i$. Rearranging the terms in (21) leads to:

$$
\begin{aligned}
\varphi_2 &\geq 1 - \frac{(p-d)^2 + 4Z_2 E}{d^2} + \frac{4E}{d^2}(Z_1 - Z_1) \\
\varphi_2 &\geq 1 - \frac{(p-d)^2 + 4Z_1 E}{d^2} - \frac{4E}{d^2}(Z_2 - Z_1) \\
\varphi_2 &\geq \varphi_1 - \frac{4E}{d^2}(Z_2 - Z_1)
\end{aligned}
$$

Knowing that, by definition, $\varphi_2 < \varphi_1$, Proposition 2 is demonstrated. $\blacklozenge$

Proof of Proposition 3.

>From (21), the firm adopts full risk internalization with technology 1 ($y_1^{LL-} < \widehat{y}_1$) if and only if:

$$
\varphi_1 \geq 1 - \frac{(p-d)^2 + 4Z_1 E}{d^2} \tag{22}
$$

and she turns to partial risk internalization after technological change iff

$$
\varphi_2 < 1 - \frac{(p-d)^2 + 4Z_2 E}{d^2} \tag{23}
$$

Having $Z_1 < Z_2$ by definition, we also have $b = \frac{(p-d)^2+4Z_2E}{d^2} > \frac{(p-d)^2+4Z_1E}{d^2} = c \geq 0$. As a direct consequence of Conditions (22) and (23), we have that $\varphi_2 < 1 - b < 1 - c \leq \varphi_1$. Point (ii) is immediate. Proposition 3 is demonstrated. $\blacklozenge$

Proof of Proposition 4.

For case a), we have to compute $E\left[\pi(y_1^{LL-})\right] < E\left[\pi(y_2^{LL-})\right]$ which is equivalent to the unlimited case presented in Proposition 1 and demonstrated above (see Equ. (20)). For case b), we must compute $E\left[\pi(y_2^{LL-})\right] - E\left[\pi(y_1^{LL+})\right] > 0$, that is:

$$
\begin{aligned}
(p - \varphi_2 d)y_2^{LL-} - Z_2(y_2^{LL-})^2 + E - (1 - \varphi_1)\left(py_1^{LL+} - Z_1(y_1^{LL+})^2 + E\right) &> 0 \\
(p - \varphi_2 d)y_2^{LL-} - p(1 - \varphi_1)y_1^{LL+} - \frac{(p - \varphi_2 d)^2}{4Z_2} + \frac{(1 - \varphi_1)p^2}{4Z_1} + \varphi_1 E &> 0 \\
p(1 - \varphi_1)y_1^{LL+} - (p - \varphi_2 d)y_2^{LL-} + \frac{1}{2}\left((p - \varphi_2 d)y_2^{LL-} - p(1 - \varphi_1)y_1^{LL+}\right) &< \varphi_1 E \\
p(1 - \varphi_1)y_1^{LL+} - (p - \varphi_2 d)y_2^{LL-} &< 2\varphi_1 E
\end{aligned}
$$

Proposition **4** is demonstrated. ♦

Proof of Proposition 5.

>From (21), we can also deduce that a firm under a limited liability rule chooses to benefit from the *ex post* legal protection if:

$$
\varphi_i < 1 - \frac{(p - d)^2 + 4Z_i E}{d^2}
$$

So we must have:

$$
\begin{aligned}
\frac{(p - d)^2 + 4Z_i E}{d^2} &< 1 \\
\Leftrightarrow p^2 - 2pd + 4Z_i E &< 0 \\
\Leftrightarrow p(p - 2d) + 4Z_i E &< 0
\end{aligned}
$$

This last inequality can only be satisfied if $p - 2d < 0$, which is Point (i).

Under unlimited liability, the firm adopts technology 2 iff (Equ. (3)):

$$
\frac{Z_2.(p - \varphi_1 d)^2 - Z_1.(p - \varphi_2 d)^2}{Z_1.Z_2} < 0
$$
$$
\Leftrightarrow p^2.(Z_2 - Z_1) - 2dp\left(Z_2.\varphi_1 - Z_1.\varphi_2\right) < d^2(\varphi_2^2 Z_1 - \varphi_1^2 Z_2) \tag{24}
$$

By using the notation $A = p.\left(Z_2.(1 - \varphi_1) - Z_1.(1 - \varphi_2)\right)$ and $d = p - \gamma$ with $\gamma \in \mathbb{R}$, this

inequality becomes:

$$A + (p - 2\gamma)(Z_1\varphi_2 - Z_2\varphi_1) < \frac{d^2(\varphi_2^2 Z_1 - \varphi_1^2 Z_2)}{p}$$

$$\Leftrightarrow A < \frac{d^2(\varphi_2^2 Z_1 - \varphi_1^2 Z_2)}{p} + (p - 2d)(Z_1\varphi_2 - Z_2\varphi_1)$$

Under limited liability, technological change occurs iff (see Equ. (27) in the Annex, case c)):

$$\varphi_1 - \varphi_2 > \frac{1}{E} \cdot \left((1 - \varphi_1) \cdot \frac{p^2}{4Z_1} - (1 - \varphi_2) \cdot \frac{p^2}{4Z_2} \right)$$

$$\Leftrightarrow p^2.(Z_2 - Z_1) - p^2\left(Z_2.\varphi_1 - Z_1.\varphi_2\right) < 4E.\left(\varphi_1 - \varphi_2\right).Z_1 Z_2 \tag{25}$$

By using the same notation $A = p.\left(Z_2.(1 - \varphi_1) - Z_1.(1 - \varphi_2)\right)$, this inequality becomes:

$$A < \frac{(\varphi_1 - \varphi_2)4EZ_1 Z_2}{p}$$

Finally, a LL rule with *ex post* legal protection gives more incentives to the firm to adopt technology 2 than a UL rule iff:

$$\frac{(\varphi_1 - \varphi_2)4EZ_1 Z_2}{p} - \left[\frac{d^2(\varphi_2^2 Z_1 - \varphi_1^2 Z_2)}{p} + (p - 2d)(Z_1\varphi_2 - Z_2\varphi_1) \right] > 0 \tag{26}$$

$$\Leftrightarrow (\varphi_1 - \varphi_2)4E > d^2(\frac{\varphi_2^2}{Z_2} - \frac{\varphi_1^2}{Z_1}) - p(2d - p)(\frac{\varphi_2}{Z_2} - \frac{\varphi_1}{Z_1})$$

This is Point (ii). Point (iii) is immediate when looking at this last inequality for E appears only in the left-hand-side term. Proposition 5 is demonstrated. ♦

Proof of Proposition 6.

By replacing p by $p_i = p - t_i$, the proof of point (i) is similar to the proof of Proposition 1. Point (ii) comes directly from inequality (16). For point (iii), consider Inequality (16)

and the derivative fo both terms with respect to $t_i, i = 1, 2$:

$$\frac{\partial}{\partial t_1}\left(\frac{(p - t_1 - \varphi_1 d)^2}{Z_1}\right) - \frac{\partial}{\partial t_2}\left(\frac{(p - t_2 - \varphi_2 d)^2}{Z_2}\right)$$

$$= -2\frac{(p_1 - \varphi_1 d)}{Z_1} + 2\frac{(p_2 - \varphi_2 d)}{Z_2}$$

$$= 4\left(\frac{(p_2 - \varphi_2 d)}{2Z_2} - \frac{(p_1 - \varphi_1 d)}{2Z_1}\right)$$

$$= 4(y_2^{tUL} - y_1^{tUL})$$

This derivative is positive (negative) if $y_2^{tUL} - y_1^{tUL}$ is positive (negative). Point (iii) follows. Proposition 6 is demonstrated. ♦

Proof of Proposition 7.

With $p_i = p - t_i$, we have $E\left[\pi(y_i^{tLL-})\right] < E\left[\pi(y_i^{tLL+})\right]$ if

$$p_i y_i^{tLL-} - Z_i (y_i^{tLL-})^2 - \varphi_i d y_i^{tLL-} + E < (1 - \varphi_i)(p_i y_i^{tLL+} - Z_i (y_i^{tLL+})^2 + E)$$

$$(p_i - Z_i y_i^{tLL-} - \varphi_i d) y_i^{tLL-} + E < (1 - \varphi_i)((p_i - Z_i y_i^{tLL+}) y_i^{tLL+} + E)$$

$$\frac{(p_i - \varphi_i d)}{2}\frac{(p_i - \varphi_i d)}{2Z_i} + E < (1 - \varphi_i)(\frac{p_i}{2}\frac{p_i}{2Z_i} + E)$$

$$(p_i - \varphi_i d)^2 - (1 - \varphi_i)p_i^2 + 4Z_i \varphi_i E < 0$$

$$\varphi_i(-2p_i d + \varphi_i d^2 + 4Z_i E + p_i^2) < 0$$

$$-2p_i d + \varphi_i d^2 + 4Z_i E + p_i^2 < 0$$

$$\varphi_i < 1 - \frac{(p_i - d)^2 + 4Z_i E}{d^2}$$

It is easy to check that $\frac{(p_i - d)^2 + 4Z_i E}{d^2} < 1$ when the optimum is $y_i^{tLL+} > \widehat{y_i^t}$. This is Point (i). Point (ii) is immediate from (19). Proposition 6 is demonstrated. ♦

Proof of Proposition 8.

Point (i) derives from the comparison of (3) and (16). Concerning point (ii), recall that a firm having adopted partial risk internalization with technology 1 turns to technology 2 and full risk internalization if $p(1 - \varphi_1)y_1^{LL+} - (p - \varphi_2 d)y_2^{LL-} < 2\varphi_1 E$ (Condition (12)). By applying it to a limited liability system with tax (p is replaced by p_i for

technology i) we obtain the following condition:

$$p_1(1 - \varphi_1)y_1^{tLL+} - (p_2 - \varphi_2 d)y_2^{tLL-} < 2\varphi_1 E$$

Replace y_2^{tLL-} and y_1^{tLL+} by their optimal value (given by (18) and (17)) in this last inequality and y_2^{LL-} and y_1^{LL+} by their optimal value (given by (7) and (6)) in (12). We obtain

$$p^2(1 - \varphi_1)Z_2 - (p - \varphi_2 d)^2 Z_1 < 4\varphi_1 Z_1 Z_2 E$$

and

$$p_1^2(1 - \varphi_1)Z_2 - (p_2 - \varphi_2 d)^2 Z_1 < 4\varphi_1 Z_1 Z_2 E.$$

Both right-hand-side terms being equal, we obtain the result of point (ii) if

$$p_1^2(1 - \varphi_1)Z_2 - (p_2 - \varphi_2 d)^2 Z_1 > p^2(1 - \varphi_1)Z_2 - (p - \varphi_2 d)^2 Z_1$$

$\Leftrightarrow$

$$(p_1^2 - p^2)(1 - \varphi_1)Z_2 - \left((p_2 - \varphi_2 d)^2 - (p - \varphi_2 d)^2\right) Z_1 \;>\; 0$$
$$(p_1^2 - p^2)(1 - \varphi_1)Z_2 - \left((p_2 - \varphi_2 d) - (p - \varphi_2 d)\right)\left((p_2 - \varphi_2 d) + (p - \varphi_2 d)\right) Z_1 \;>\; 0$$
$$(p_1^2 - p^2)(1 - \varphi_1)Z_2 - (p_2 + p - 2\varphi_2 d)(p_2 - p) Z_1 \;>\; 0$$

Recall that $p_1 = p - t_1$ and $p_2 = p - t_2$. Thus:

$$((p - t_1)^2 - p^2)(1 - \varphi_1)Z_2 + (2p - t_2 - 2\varphi_2 d) t_2 Z_1 \;>\; 0$$
$$t_1(t_1 - 2p)(1 - \varphi_1)Z_2 + t_2\left(2(p - \varphi_2 d) - t_2\right) Z_1 \;>\; 0$$
$$\frac{t_1(t_1 - 2p)(1 - \varphi_1)}{t_2\left(t_2 - 2(p - \varphi_2 d)\right)} \;>\; \frac{Z_1}{Z_2}$$

Proposition 8 is demonstrated. ♦

Other cases (c et d) complementing Proposition 4, page 11.

Proposition 9 *c) A firm having adopted partial risk internalization with technology 1 turns to technology 2 while keeping partial risk internalization if:*

$$E.(\varphi_1 - \varphi_2) > (1 - \varphi_1).\frac{p^2}{4Z_1} - (1 - \varphi_2).\frac{p^2}{4Z_2} \tag{27}$$

or

$$E.(\varphi_1 - \varphi_2) > (1 - \varphi_1)Z_1(y_1^{LL+})^2 - (1 - \varphi_2)Z_2(y_2^{LL+})^2$$

d) A firm having adopted full risk internalization with technology 1 turns to technology 2 and partial risk internalization if:

$$p(1 - \varphi_2)y_2^{LL+} - p(1 - \varphi_1)y_1^{LL-} > 2\varphi_2 E \tag{28}$$

Proof.

For case c), we have to compute $E\left[\pi(y_1^{LL+})\right] < E\left[\pi(y_2^{LL+})\right]$, that is:

$$(1 - \varphi_1)(py_1^{LL+} - Z_1(y_1^{LL+})^2 + E) - (1 - \varphi_2)(py_2^{LL+} - Z_2(y_2^{LL+})^2 + E) < 0$$

By replacing y_1^{LL+} and y_2^{LL+} by their value given by Equ. (6), and after simplification and arrangement,we have:

$$E.(\varphi_1 - \varphi_2) > (1 - \varphi_1).\frac{p^2}{4Z_1} - (1 - \varphi_2).\frac{p^2}{4Z_2}$$

or

$$E.(\varphi_1 - \varphi_2) > (1 - \varphi_1)Z_1(y_1^{LL+})^2 - (1 - \varphi_2)Z_2(y_2^{LL+})^2$$

For case d), we must compute $E\left[\pi(y_1^{LL-})\right] < E\left[\pi(y_2^{LL+})\right]$, that is:

$$
\begin{aligned}
(p - \varphi_1 d)y_1^{LL-} - Z_1(y_1^{LL-})^2 + E - (1 - \varphi_2)(py_2^{LL+} - Z_2(y_2^{LL+})^2 + E) &< 0 \\
\frac{(p - \varphi_1 d)^2}{2Z_1} - (1 - \varphi_2).\frac{p^2}{2Z_2} - \frac{(p - \varphi_1 d)^2}{4Z_1} + (1 - \varphi_2).\frac{p^2}{4Z_2} + \varphi_2 E &< 0 \\
\frac{(p - \varphi_1 d)^2}{4Z_1} - (1 - \varphi_2).\frac{p^2}{4Z_2} + \varphi_2 E &< 0 \\
Z_2(p - \varphi_1 d)^2 - (1 - \varphi_2)Z_1 p^2 + 4Z_1 Z_2 \varphi_2 E &< 0 \\
p(1 - \varphi_2)y_2^{LL+} - (p - \varphi_1 d)y_1^{LL-} &> 2\varphi_2 E
\end{aligned}
$$

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