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The Efficiency of (strict) Liability Rules revised in Risk and Ambiguity[1]

Nicolas LAMPACH [3] and Sandrine SPAETER [2]

Abstract

In this paper we revise the results about the efficiency of (strict) unlimited, then limited liability in inducing optimal investment in prevention by injurers. Risk and ambiguity are considered. We assume that the potential injurer whose activities cause a risk of environmental accident can reduce the probability of accident by investing in prevention. In the risky model, we recover that limited liability does not always induce low prevention. Contrary to the arguments enhanced by Beard (1990) and Lipowski-Posey (1993), outside lending but absent from our model, does not explain this result. In the ambiguous context, we implement the Non-Extreme Outcome (NEO) expected utility model (Chateauneuf et al., 2007) to represent the injurer's beliefs and decisions. When ambiguity matters and prevention affects the injurer's subjective beliefs none of the results with risk hold. In particular, the injurer can overinvest in prevention under both unlimited and limited liability.

JEL classification: K0; K32; D81; D29

Key words: Strict liability; Ambiguity; Optimal Care; Optimism; Subjective Beliefs.

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1 Introduction

Major environmental disasters involving dangerous chemicals, severe oil spill or hazardous substances pose a threat to humans and the environment. In the course of past decades, several disasters can be relegated to errors or lack of prevention done by injurers[1]. In Europe, the catastrophic accident in the Italian town of Seveso in 1976 was the trigger for the adoption of the legislation by the European Council in 1986 on the control and prevention of such accidents. In the United States, the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA) has been adopted to prevent contamination of future sites by designating strict and, for certain cases, extended liability to involved agents.

Nowadays, policy-makers are enacting laws on new emerging technologies, likewise genetic modified organism, nanotechnology or shale gas by taken into account the Precautionary Principle[2] (PP). For instance, the European Commission, as the regulator initiating and enforcing EU laws, uses the PP to cope with possible risks for which scientific knowledge is not fully available. UNESCO (2005) reports common elements, concepts and definitions regard the PP. The report underlines that risks with poorly known outcomes and poorly known probability is sufficient to foresee the consideration of the PP. It should be emphasized that the regulator turns the burden of proof[3] to the injurer by requiring a sophisticated risk assessment on the potentially risks of the new emerging technology.

Tort and liability rules as an environmental policy instrument pursue to give injurers an incentive to internalize the social cost of their taken actions (Brown, 1973; Calabresi, 1970). In general, liability rules engage injurers to restore or compensate for damages caused by their activities. An important feature of the literature on tort law has focused on the efficiency of different liability rules, likewise negligence and strict[4] (limited and unlimited) liability under the assumption that injurers know the relevant probabilities.

In law and economics, an extensive literature exists on analyzing the efficiency of liability rules by comparing the negligence and the strict and unlimited liability rules under risk.[5]. However, we wonder how the current existing legislation, especially tort law, deals with new emerging technologies. This question is motivated by the current debate on the performance of liability rules in sectors using nanotechnologies. The European Commission adopted the 18th October 2011 (Commission Recommendation 2011/696/EU) the international definition of *nanomaterials* for regulatory purposes. Nanomaterials are applicable under the general scheme of the European Environmental Liability Directive (ELD) ANNEX III. However, the ELD does not include specific provisions for nanomaterials. In the US, federal environmental regulation of engineered nanomaterials is most likely to occur under the Toxic Substances Control Act, the Federal Insecticide, Fungicide and Rodenticide Act, the Resource Conservation and Recovery Act, the Comprehensive Environmental Response Compensation and Liability Act (John and Van Calster, 2010).

[1] In this paper, the firm is the potential injurer.

[2] Second paragraph of Article 191 of the Treaty on the Functioning of European Union (Maastricht Treaty).

[3] In the European law context, the regulator is acting on the basis of the *"guilty until proven innocent"* approach. See Van der Belt (2003) for more details. More generally, see Kayikci (2012) on the burden of proof within the scope of the Precautionary Principle in the international and European context. More specifically, see German Advisory Council on the Environment (2011) on the Precautionary Principle in the context of managing nanomaterials.

[4] Strict liability is deemed to impose absolute legal responsibilities on the injurer without proof of fault or negligence.

[5] See Landes and Posner (1987), Posner (1992) and Shavell (2004) for textbooks on liability rules. See also Schaefer and Mueller-Langer (2009), Halbersberg and Guttel (2014) and Faure (2010) who outline liability rules in the context of behavioral accident law and economics.

Of particular interest are the reports by the U.S. Environmental Protection Agency in August 2010 and the Scientific Committee on Emerging and Newly Identified Health Risks (SCENIHR) in June 2014, stressing possible environmental and health effects due to the application of nanosilver (AG-NP) in medical care (for instance, wound dressings such as bandages or as coatings for medical devices) and in consumer products (e.g., sport textiles, cosmetics, washing powder and deodorants). The Scientific Committee and the Environmental Protection Agency underline that more information is required on the possible contribution of AG-NPs to environmental and human toxicity. Additionally, more information is needed on the probability of the release of nanosilver[6].

In Europe, but also in the United States, the liability rule that caps the financial liability of the injurer to the value of her net assets at the moment of the accident is widely applied: it is called limited liability. Potential injurers are called, in such a situation, judgment proof firms. In the literature on law and economics, it has also been widely studied (Beard (1990), Grundfest (1992), Lipowski-Posey (1993), Pitchford (1995), Dari-Mattiacci and De Geest (2005), Dari-Mattiacci and De Geest (2006), Jacob and Spaeter (2015) among others). On one hand, strict limited liability is known as being a regime that induces partial risk internalization by potential injurers and encompasses an *ex-post* cap payment for the shareholders (Shavell, 1986). On the other hand, limiting the potential injurers' liability to their net present value amplifies innovation and permits them to levy funds for research and development. In contrast, (strict) unlimited liability is often considered as the rule that shall induce full compensation of victims. Nevertheless, strict and unlimited liability may also lead to price increases and may push some firms out of the market even though they took all required precautionary measures (Manning, 1994).

In well-known risky environments, these theoretical results are established and widely applied. The aim of this paper is to demonstrate that these results should be put in doubt as soon as risk cannot be perfectly defined, as it is more and more frequently the case when dealing with new emerging products or processes. In that case, we have to deal with (scientific) uncertainty or ambiguity.

With Ellsberg (1961) thought experiments, the necessary foundations on revealing the importance of attitudes toward ambiguity has been laid down[7]. Ambiguity has become a central issue in the management and regulation of new emerging risks. Nevertheless, a few papers deal with the question of ambiguity related to tort law. Jacob (2015) mainly studies the situation in which the potential injurer's insolvency alters her technical choice when facing the possibility of a new and imprecise technology. Pannequin and Ropaul (2015) focus on the effect of strict liability and negligence rule on the demand for both insurance and self-insurance.

Closest to our paper are Mondello (2013), Chakravarty and Kelsey (2016) and Teitelbaum (2007). Under ambiguity, these three papers assume that the injurer is a choquet expected utility maximizer who forms beliefs about accident risk by using a special kind of capacity, called a neoadditive capacity. Further, they focus on the negligence rule and (strict) unlimited liability[8].

[6] AG-NP remains a fairly poorly understood material (Federal Institute for Risk Assessment (2009), Environmental Protection Agency (2010), Ray et al. (2010), Seltenreich (2013) and SCENIHR (2014)).

[7] For a more detailed discussion on developments in modelling preferences under ambiguity, see Camerer and Weber (1992) and, more recently, Etner et al. (2012).

[8] Dari-Mattiacci and De Geest (2005) refer to four different precaution models when risk is considered. Teitelbaum (2007) implements two models (Probability and joint-probability model) in his analysis, whereas Chakravarty and Kelsey (2016)

Teitelbaum (2007) shows that neither strict liability nor the negligence rule is efficient when ambiguity is at stake. He finds that negligence is more robust than strict liability. Mondello (2013) considers the situation in which the judge and the regulator agree on the optimal social level of care. Still in this setting, neither strict liability nor the negligence rule permits it to reach the first best level of care under ambiguity. Chakravarty and Kelsey (2016) shows that an ambiguity averse injurer invests the optimal amount in prevention under the negligence rule but invests more in prevention than the social optimal level under strict and unlimited liability.

In line with Mondello (2013), Chakravarty and Kelsey (2016) and Teitelbaum (2007), we analyze the efficiency of liability rules for situations where the injurer has inherently scarce knowledge about the probabilities of an accident to occur. We focus on the strict liability rule and we consider especially both regimes, unlimited and limited liability. To the best of our knowledge, this is the first work that shows how the potential injurer's behavior is affected by limited liability in the presence of ambiguity in the unilateral accident model. Moreover, in the abovementioned studies it is implicitly assumed that prevention only impacts the objective probability of accident anounced by the regulator. In this paper, we presume that the subjective and personal belief built by the injurer depends on her degree of optimism but also on her investment in prevention.

We apply the (NEO-EU) model axiomatized by Chateauneuf et al. (2007) to embrace ambiguity in the basic unilateral accident model. The injurer assigns a degree of confidence to the preliminary probability of accident announced by the regulator. Furthermore, she builds simultaneously her own beliefs, which is considered with the complementary degree of confidence and her degree of optimism/pessimism. This last indicator gives also information about the injurer's ambiguity attitude.

We show that none of the results with risk hold when ambiguity matters. In particular, the injurer tends to overinvest in prevention whenever she believes that she is able to better control for her "self-constructed" weight on the accident state than the regulator does with the preliminary probability. This result holds for both unlimited and limited liability. In the risk section, we also show that the injurer may invest more in prevention under limited liability.

The remainder of this article is organized as follows. Section 2 presents the unilateral accident model and discusses the debate around "private level of prevention vs. social level of prevention". Section 3 explains how ambiguity about accident risk is performed in the framework of NEO-expected utility model and states the results of the model. Section 4 concludes the paper. Proofs are presented in the appendix.

2 The Basic Model

The model is based on the unilateral accident model proposed by Shavell (1980). There are two agents, a potential injurer (a firm whose activity is risky for Society for instance) and a representative victim. The utility of the firm's activity is assumed to have an equivalent in terms of income. We assume that both parties are risk-neutral such as expected income equals expected utility[9]. The injurer's activity yields a risk of accident. An accident entails a damage L with realization in $[0, l]$, $l > 0$. We denote as d

discuss apart on one model (Magnitude model).

[9]Risk aversion does not affect the results about the (in)efficiencies of liability rules with regard to prevention.

the payment made by the injurer to the victim if an accident occurs: We have $0 < d \leq l$ in case of strict liability, and $d = 0$ in case no liability rule is put in place. In the absence of liability, all accident losses fall on the victim and no compensation fee will be paid by the injurer. The probability π of an accident, with $\pi \in [0, 1]$, depends on the monetary amount[10] x invested by the injurer in prevention, with $x \in [0, \overline{x}]$ and $\overline{x} > 0$. We assume $\pi'(x) < 0$ and $\pi''(x) > 0$. The potential injurer makes a net benefit b over the production of quantities[11].

At this point, it shall be emphasized that neither causation, nor administrative or litigation costs are taken into account in the model. The potential injurer does not purchase liability insurance.

The regulator is in charge of maximizing the expected social welfare in a simple probability model. According to Dari-Mattiacci and De Geest (2005), the injurer can reduce the probability of accident by taking appropriate prevention measures, while the magnitude of the harm is not being affected.

The social expected welfare $E(\tilde{W^S})$ is the sum of the injurer's profit and the expected costs of damage borne by Society. The regulator's program writes $\max_x E(\tilde{W^S}) = b - \pi(x)l - x$. Since b is independent of the prevention level x, this program is equivalent to the following cost minimization program:

$$\min_x E(\tilde{C^S}) = \pi(x)l + x \tag{1}$$

For an interior solution, the social optimal level of prevention x^S that shall be enforced by a regulator satisfies:

$$-\pi'(x^S)l = 1 \tag{2}$$

The left (right)-hand-side term is the well-known expected marginal benefit (cost) of prevention. The former corresponds to the reduction in the expected value of the loss following a one-unit investment in prevention. The latter corresponds merely to one monetary unit invested in prevention.

Now, let us consider the private decision taken by the potential injurer. In this section, we consider the main results at stake with strict liability[12] when the risk is perfectly known by both parties and liability is successively unlimited as well as liability is limited to the net value of the potential injurer. Unlimited (respectively limited) liability is formalized by a payment $d = l$ (respectively $0 < d < l$) by the potential injurer to the victim in case of an accident. When unlimited liability holds, the injurer will always have to pay for the whole damage induced by her activity: $d = l$. In the case of limited liability, the payment to the victim is capped by the net value of the firm so that the required compensation to be paid may be lower than the damage. As a consequence the potential injurer is pushed into bankruptcy. We are particularly interested in this last case, so that we assume that $d < l$: Meaning that the damage is always higher than the net value of the potential injurer confiscated for compensation when an accident occurs.

[10]See for instance Macminn (2002) and Miceli and Segerson (2003) who compare the negligence rule with strict liability by distinguishing between non-monetary and monetary cost of care.

[11]We suppose that the level of activity is exogenous and constant so that profit maximization will be equivalent to cost minimization in many cases (but not always as we will show later on).

[12]We do not consider the negligence rule in this paper. It has been extensively analyzed, for instance, in Shavell (1980), Brown (1973), Miceli and Segerson (2003), Teitelbaum (2007), Chakravarty and Kelsey (2016), and Mondello (2013).

2.1 Private optimum when strict and unlimited liability holds

Under the rule of strict liability an injurer is held liable when she causes a harm even if she is not being found negligent (Shavell, 2004). Under the regime of unlimited liability an injurer has to pay *ex post* for all the damage caused by her activity whatever her level of prevention. The damage needs to be fully compensated even if it exceeds the net wealth of the injurer. As a result, the injurer's profit can be negative, and the victims do not have, *ex ante*, to bear the financial damage caused by the injurer. Accordingly, the injurer is required to internalize the full expected cost of accident. Hence her private program is

$$\min_x E(\tilde{C^P}) = \pi(x)l + x \tag{3}$$

This private program (3) fits with the social one (1). As a consequence, the optimal private level of prevention x^P_{UL} equals the social one x^S. When the risk is perfectly known and the injurer can be identified as wrongdoer, strict and unlimited liability is presented as an efficient regulatory tool regarding the optimal level of prevention; both induce full risk internalization by the potential injurer.

This is no longer the case when liability is limited to the net value of the potential injurer. Contrary to the first intuition and to some results of the literature (Pitchford (1995), Faure (1995)) we show that underinvestment in prevention is not systematically observed with limited liability. This result was also obtained by Beard (1990) and Dionne and Spaeter (2003), but by introducing an outside lender in the model. We show that this third party is not needed to obtain the result.

2.2 When the *ex post* potential injurer's liability is limited to her net value

Consider now the case of strict but limited liability, where the injurer is still liable for the harm she causes. However, her payment is limited to the net value of the potential injurer, which can never be negative under this regime. Let us assume that the loss l in case of an accident is always higher than the maximum possible value of the potential injurer: $b < l$. Let us denote the injurer's private wealth as $W^P_{LL} = b - x - \hat{d}$ in the accident state and $W^P_0 = b - x$ in the no accident state. The level $\hat{d}$ is the maximum amount of damage that an injurer pays given her level of prevention. Hence, we have $\hat{d} = b - x < l$ and $W^P_{LL} = 0$. Such as in Dari-Mattiacci and De Geest (2005) and in Jacob and Spaeter (2015), the level of damage that pushes the potential injurer into bankruptcy is endogenous in the model: choosing x implies also choosing $\hat{d}$. We have $\hat{d} = \hat{d}(x)$. Finally, the injurer considers the following private program:

$$\begin{aligned}\max_x E(\tilde{W^P_{LL}}) &= (1 - \pi(x))W^P_0 \\ &= (1 - \pi(x))\hat{d}(x)\end{aligned} \tag{4}$$

Contrary to the preceding case, the profit maximizing program cannot be replaced by a cost minimizing program although the benefit b does not depend on x. Actually, it enters into the available funds for compensation in case of an accident and thus cannot be removed. Contrary to what is considered in

Dari-Mattiacci and De Geest (2006), profit maximization is no longer equivalent to cost minimization under limited liability. With $\hat{d}(x) = b - x$, the first order condition of Program (4) for an interior solution x_{LL}^P is:

$$-\pi'(x_{LL}^P)\hat{d}(x_{LL}^P) = 1 - \pi(x_{LL}^P) \tag{5}$$

We obtain the following results.

Proposition 1 *Let us assume that the injurer is an expected utility maximizer and the bankruptcy threshold $\hat{d}$ is endogenous to the model*

(i) The injurer can invest either more or less in prevention than the social optimal level. Formally $x_{LL}^P \lesseqgtr x^S$ in optimum.

(ii) Whenever over-investment in prevention is observed, this does not imply social welfare improvement.

A comparison of (5) with (2) yields the following comments. Both the expected marginal benefit (left-hand-side term) and the marginal cost (right-hand-side term) of prevention are affected by the introduction of limited liability. Indeed, as part $(l - \hat{d})$ of the loss is externalized toward the victims, the marginal benefit of prevention expected by the injurer decreases: $0 < -\pi'(x)\hat{d}(x) < -\pi'(x)l$ for any x. In the meantime, the marginal cost of prevention also decreases: $0 < 1 - \pi(x) < 1$. In fact one monetary unit invested in prevention will only be costly for the injurer whenever there is no accident. In the accident case, all assets net of prevention costs are confiscated and the potential injurer's profit falls to zero. Hence part of the cost of prevention is recovered by the potential injurer since they are deduced from her assets before compensation. As a direct consequence, it could be profitable for her to invest even more in prevention than the social optimum. Finally, contrary to the first intuition, limited liability does not imply systematic underinvestment in prevention. Whenever the marginal cost declines more rapidly than the expected marginal benefit, the potential injurer invests more in prevention than the social level. This result was obtained by Beard (1990) and Lipowski-Posey (1993). Dionne and Spaeter (2003) under limited liability for the potential injurer while considering extended liability for the bank[13] which finances the potential injurer. In these three papers, an outside lender is financing the firm, so that the latter loses part of the money of the bank when she is pushed into bankruptcy. In our setting, there is no external lender. The fact that victims have to bear part of the loss can be considered as extending the (financial) liability toward them[14]. Whenever the firm decides her level of prevention x, she also decides her level of bankruptcy $\hat{d}(x)$, as a direct consequence the level of loss $l - \hat{d}(x)$ is borne by the victims after compensation. Finally, the firm's decision x has a simultaneous impact on the probability of accident $\pi(x)$ and the magnitude of the non-compensated loss $l - \hat{d}(x)$.

The result of Point (i) of Proposition 1 stands in contrast with the widespread conclusion on underinvestment in prevention (or care) when liability is limited. Actually, this well-known result of the literature has been obtained in a cost minimizing setting. In such a framework, the level of damage that pushes the

[13] The bank must pay for the extra damage whenever the potential injurer is pushed into bankruptcy and cannot fully compensate the victims.

[14] See also Dari-Mattiacci and De Geest (2006).

potential injurer into bankruptcy is exogenous in the model (Shavell, 1986). Thus maximizing expected profit with $\hat{d}$ exogenously fixed is equivalent to minimizing the expected costs of prevention $\pi(x)\hat{d} + x$. The solution to this program is clearly a level of prevention strictly lower than the social one. Unfortunately, as shown above profit maximization does no longer correspond to cost minimization under limited liability.

Result (ii) is rather immediate. When the injurer decides to invest a level x_{LL}^P in prevention higher than the social level x^S, she decreases *ex ante* the probability of accident below the level $\pi(x^S)$. In the meantime, she also deteriorates the conditions of the *ex post* compensation by reducing the available funds for compensation. And if such a strategy is optimal for her, it is suboptimal for the victims since what is earned by the former due to partial risk internalization is lost by the latter.

The suboptimality of limited liability compared to unlimited liability can be discussed further when relaxing the hypothesis of well-known risks. In other words, strict and unlimited liability does no longer perform so well when considering scientific uncertainty or, more generally, new and not yet well-defined risks or technologies. We focus on this point in the next section.

3 Efficient rules with ambiguity

In the seminal contribution by Ellsberg (1961) and in ensuing experiments, it has been acknowledged that the perception of unavailable information affects individuals' choice behavior. Note that various definitions of ambiguity are provided by the literature. (See for further details, and among other papers, Ellsberg (1961), Frisch and Baron (1988), Nehring (1999), Teitelbaum (2007), Barham et al. (2014), Epstein (1999) and Epstein and Zhang (2001). See also Etner et al. (2012) for a recent survey on ambiguity and decision theory.)

In this section, we use the NEO-expected utility (NEO-EU) model axiomatized by Chateauneuf et al. (2007) to embrace ambiguity in the basic unilateral accident model. NEO-EU is a special case of Choquet expected utility model (Gilboa, 1987; Schmeidler, 1989) with a Non-Extreme-Outcome additive (NEO-additive) capacity. The name comes from the fact that NEO-additive capacities are additive for events yielding non-extreme outcomes. More generally, non-additive probabilities or capacities reflect the individual's beliefs about the likelihood of uncertain events. Individuals maximize an expected utility function with respect to a capacity instead of a probability distribution (Mondello, 2013).

Situations in which an individual behaves as if she had an additive probability distribution, albeit doubts whether this distribution is the true one can be captured by a NEO-additive capacity. Both doubt and reaction to doubt are parameterized, representing the degree of ambiguity and the individual's attitude toward it (Dominiak and Lefort, 2013). Chateauneuf et al. (2007) introduce a specific weighting scheme to model ambiguity. NEO-additive capacity can be viewed as a linear combination of an additive capacity and a particular (non additive) capacity, named Hurwicz capacity that only distinguish between whether an event is impossible, possible or certain.

A NEO-additive capacity is a non-additive belief that represents a deviation from an additive belief, such that the degree of ambiguity measures the lack of confidence the individual has in some additive probability distribution (Romm, 2014). In the NEO-EU model, optimism and pessimism are defined with respect to the weights the individual applies to the extreme outcomes, which embed attitudes toward ambiguity: A concave capacity reflects optimism (ambiguity loving), while a convex capacity reflects pessimism (ambiguity seeking) (Schmeidler (1989), Wakker (2001), Chateauneuf et al. (2007)). Also, for the sake of comparison to previous works (Chakravarty and Kelsey (2016), Teitelbaum (2007), Mondello (2013)) we apply the NEO-EU model to our issue.

To illustrate our principal idea, let us recall our previous example about the issue of the uncertain evidence in the nanoscience. New nanotechnology products are hitting the market and, in the meantime, consumers and the environment are exposed to an uncertain risk. The regulator considers his currently available information on the likelihood of an accident related to the new technology as sufficient to approve the new products for sale. In other words, we purport that the regulator has sufficient preliminary scientific information on a small probability of accident to approve the new products. However, some scientific committees, agencies and scientists enhance the fact that these new products could have negative long-term effects on human health and the environment. They report that further scientific expertise is required. Since the knowledge about methodologies and the lack of analytical techniques for evaluating potential long-term risks are not available, no proof can yet be assigned.

Let us assume that ambiguity matters in a way we have described above and the injurer is a NEO-EU maximizer whose beliefs about the "preliminary" probability π of an accident announced by the regulator can be represented by a behavior-additive capacity (Chateauneuf et al., 2007). The injurer believes that this so-called preliminary probability π is the true probability with a degree of confidence δ, with $\delta \in [0, 1]$. As an illustration, on one hand the injurer believes with a given degree δ of confidence that nanosilver in medical care and products would have a negative impact on human body that can be evaluated by the probability π announced by the regulator. On the other hand, another level of risk shall not be ignored, and is considered with a degree of confidence $1 - \delta$. Besides the chance of bearing a loss in this second scenario and evaluated by the injurer depends on her degree of optimism/pessimism[15].

Let us denote as α this degree of optimism with $\alpha \in [0, 1]$. We consider that the injurer is optimistic when $\alpha > 0.5$, pessimistic when $\alpha < 0.5$ and ambiguity neutral when $\alpha = 0.5$. We still denote as $q(\alpha, x)$ the belief built by the injurer on the accident state in the second scenario, with $q_\alpha < 0, q_x \leq 0$ and we assume that $q(\alpha, 0) \lesseqgtr \pi(0)$ for $\alpha \lesseqgtr 0.5$. It depends on her degree of optimism as explained above, and also on her investment in prevention. This assumption is different from what is considered in Teitelbaum (2007), Chakravarty and Kelsey (2016) and Mondello (2013). Indeed, these authors assume that prevention (or care) only impacts the probability, π, which we deem is a rather strong assumption. We consider a more general, and potentially more realistic, situation in which the injurer can also impact uncertainty by investing in prevention. Figure 1 presents the compound ambiguous and risky lottery.

[15]There exist no generally accepted definitions of optimism and pessimism. The most popular used in the psychology literature is Scheier and Carver (1985)'s definition who states that optimism and pessimism are two different concepts and are forms of positive and negative illusions. See also, Chang et al. (1997), Pulford (2009), Dember et al. (1989), Hecht (2013) and Koebel et al. (2016). In this paper, we consider confidence and optimism as a character trait.

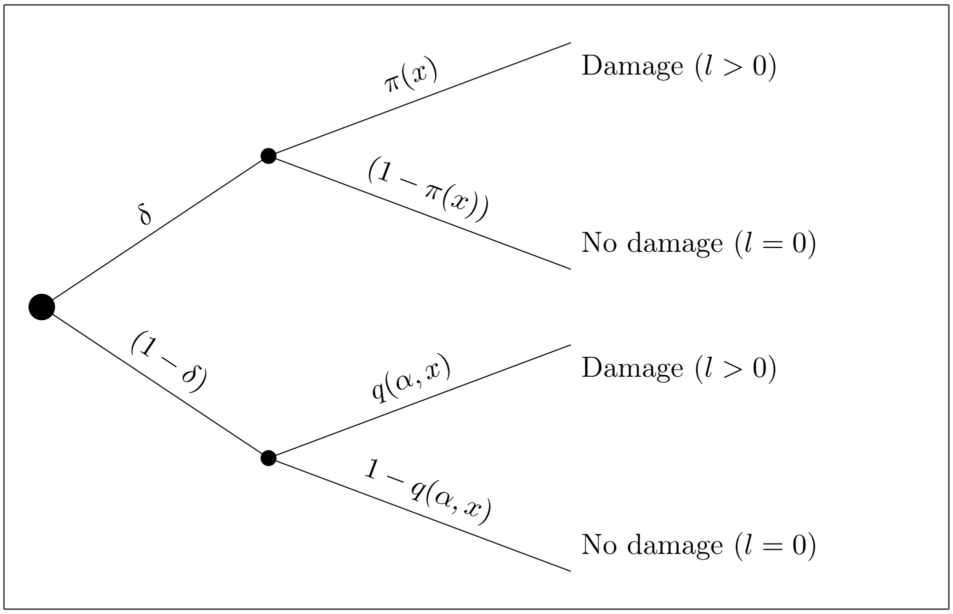

Figure 1: Compound ambiguous and risky lottery

3.1 Private optima and ambiguity

The injurer's objective remains to maximize her expected net profit and the expected costs caused by engaging in a risky, but now also ambiguous activity. Let us recall that the level of compensation paid by the potential injurer in the state "accident" is $d = 0$ (respectively $d = \widehat{d} < l$, $d = l$) when no liability (respectively strict but limited liability, strict and unlimited liability) holds for the injurer.

3.1.1 Strict and unlimited liability

Under strict and unlimited liability, the injurer computes the following program:

$$\max_x E(\widetilde{W_{UL}^{amb}}) = \delta[\pi(x)(b-x-l) + (1-\pi(x))(b-x)]$$
$$+ (1-\delta)[q(\alpha,x)(b-x-l) + (1-q(\alpha,x))(b-x)]$$

After simplifying, we obtain the following program:

$$\max_x E(\widetilde{W_{UL}^{amb}}(x)) = b - x - [\delta\pi(x) + (1-\delta)q(\alpha,x)]l \tag{6}$$

Proposition 2 *Let us assume that the injurer is a NEO-EU maximizer*
i) If her belief about the accident state in the non-confident scenario is independent of her level of prevention, then she always invests less in prevention than in the risky, but non ambiguous environment. Formally if $q_x = 0$ *then* $x_{UL}^{amb} < x_{UL}^P = x^S$*.*
ii) In the more general case where $q_x < 0$*, the injurer invests more in prevention than the social optimum if the probability of accident announced by the regulator is less sensitive to prevention than her own subjective belief. This result holds whatever her degree of confidence in the regulator's announcement. Formally*

we have $x_{amb}^{UL} \lesseqgtr x^S$ *iff* $\left|\pi'(x^S)\right| \gtreqless \left|q_x(\alpha, x^S)\right|$, $\forall\delta < 1$.

iii) The more optimistic the injurer, the higher (lower) her private level of prevention if and only if $q_{x\alpha} < 0$ (> 0).

Proof. See Appendix. ■

Point i) is rather immediate. It fits with the framework proposed by Teitelbaum (2007), Chakravarty and Kelsey (2016) and Mondello (2013): the subjective belief of the injurer is not affected by prevention. Thus the only probability that matters is the preliminary one π. As the impact of prevention on this probability π is only considered with a degree of confidence $\delta < 1$, the marginal benefit of prevention is lower than in the preceding case with risk but without any ambiguity. Thus in this setting, the private level of prevention is always lower than the social one obtained with risk knowing that the marginal cost of prevention remains unchanged.

Point ii) is far more interesting for it considers also the possibility for the injurer to control her personal and subjective belief by investing in prevention. We deem that if the injurer can influence the preliminary objective probability π, she also beliefs that she can influence her subjective belief q.

The level that the injurer will invest in optimum depends on the relative efficiency of prevention on the probability $\pi(.)$ and the weight $q(\alpha, .)$. Two important points shall be noticed. First, the fact that the injurer invests either more or less in prevention than the social optimum does not depend on her degree of confidence δ. Indeed even if the injurer is highly confident (high δ) in the announcement π made by the regulator she will underinvest in prevention if her personal belief q (considered with a degree of confidence $1 - \delta$) is relatively insensitive to prevention. The explanation is straightforward: In the first scenario the announcement of π made by the regulator is considered as identical to the scenario under risk. Thus this first scenario yields the same unit marginal benefit and unit marginal cost as in the situation with risk. The changing point is that a second scenario emerges in the ambiguity case: The possibility that the injurer considers simultaneously a subjective belief q of accident. In this second scenario, she compares the sensitivity of q to x with the sensitivity of π to x whatever her degree of confidence over this second scenario.

The second important point that shall be noticed deals with the optimal private level of prevention. In the ambiguous case, the injurer may overinvest in prevention compared to the social level under unlimited liability, whenever she believes that she is able to better control "her" probability q through prevention than the regulator does with π. It seems amazing to consider that a character trait, like optimism, can have an impact on the sensitivity of a probability or a weight, here the accident weight $q(.,.)$. Now recall that $q(.,.)$ is a subjective belief built by the injurer. Hence it seems actually fair to consider that an optimistic individual may not only relativize the risk of accident (by considering, for instance, a small weight q on the accident state), but also believes that she can have some control on it. This can be illustrated by a function q that satisfies $q_{x\alpha} < 0$. The more optimistic the injurer the higher is her belief about her ability to control the (subjective) probability of accident through prevention. In such a setting we obtain a higher level of prevention from an optimistic injurer[16].

[16]Let us still notice that the coefficient α is also seen in some models as the parameter that measures the attitude toward ambiguity: pessimism (low α) is related to ambiguity aversion. If such an interpretation were considered in our model, it would mean that ambiguity averse injurers invest less in prevention.

3.1.2 Strict but limited liability

Now let us consider strict but limited liability in the NEO-EU model. Recall that we have denoted $W_{LL}^P = b - x - d$ as the worst realization of wealth for the injurer and $W_0^P = b - x$ as the best one (no accident). Under limited liability, we have $\widehat{d} = b - x < l$ and $W_{LL}^P = b - x - \widehat{d} = 0$. The injurer's maximization program writes

$$\begin{aligned} \max_x E(\widetilde{W_{LL}^{amb}}(x)) &= \delta[\pi(x)W_{LL}^P + (1-\pi(x))W_0^P] + (1-\delta)[q(\alpha,x)W_{LL}^P + (1-q(\alpha,x))W_0^P] \\ &= [(1-\delta)(1-q(\alpha,x)) + \delta(1-\pi(x))](b-x) \end{aligned} \tag{7}$$

In this expected wealth, only the no accident state matters since no wealth is available in the accident state: all the assets are confiscated for compensation such as previously in the risky environment. The total expected wealth $E(\widetilde{W_{LL}^{amb}}(x))$ corresponds to the sum of the expected wealth considered both in the first scenario (confident scenario) and in the second one (non-confident scenario). Consider the following notation:

$$j(\alpha,\delta,x) = (1-\delta)(1-q(\alpha,x)) + \delta(1-\pi(x)) \tag{8}$$

Function $j(x)$ plays the role of a synthetic weight put by the injurer on the no-accident state. It depends on the personal trait such as α, personal beliefs δ and individual decision x. Recall that under risk, only limited liability may yield such a result. For an interior solution x_{LL}^{amb} and with $\widehat{d}(x) = b - x$, the first-order-condition of Program (7) is:

$$j_x(\alpha,\delta,x_{LL}^{amb})\widehat{d}(x_{LL}^{amb}) = j(\alpha,\delta,x_{LL}^{amb}) \tag{9}$$

Now, let us compare this first-order-condition with the one that prevails under risk, that is with (5). It writes:

$$\left|\pi'(x_{LL}^P)\right| \hat{d}(x_{LL}^P) = 1 - \pi(x_{LL}^P) \tag{10}$$

In both first-order-conditions, the left-hand-side term is the expected marginal benefit of prevention, while the right-hand-side term is the expected marginal cost of prevention. In both cases, the expected marginal cost of a one unit expense is no longer one. Indeed, this one unit expense impacts the available wealth of the injurer only in the no accident state, which occurs with probability $(1-\pi(x))$ in the risky situation, while it is weighted by the subjective synthetic weight $j(\alpha,\delta,x)$ in the model with ambiguity. While moving from risk to ambiguity, the variation of the expected marginal cost of prevention depends simultaneously on the injurer's degree of optimism/pessimism α and degree of confidence in the regulator's announcement. In the meantime, the expected marginal benefit in case of ambiguity is affected by the degree of confidence and the ambiguity attitude of the injurer, but not only. The efficiency of the prevention technology also matters. This is captured by $j_x(\alpha,\delta,x_{LL}^{amb})$ in (9) and by $\left|\pi'(x_{LL}^P)\right|$ in (10). Finally, several different configurations are at stake when considering the injurer's ambiguity attitude, degree of confidence and belief in her ability to control through prevention and the subjective probability of accident she built in the non-confident scenario.

Proposition 3 *Let us assume that a regime of limited liability holds and that the injurer is a NEO-EU maximizer. (i) It is not possible to conclude about the optimal level of prevention under ambiguity compared to risk, whatever the agent's level of confidence and degree of optimism, even though* $j_x(\alpha, \delta, .)$ *and* $|\pi'(.)|$ *can be ranked.*

Proof. See Appendix. ■

This result reinforces Point (ii) of Proposition 2 presented in the model with risk: limited liability does not always restrict prevention. Many different cases are possible. As it states, without constraining the design of the probability functions used in our model, we are not able to isolate a case as more plausible than another one (for instance, more prevention than the unlimited liability level).

Our results are different from those proposed by the existing literature on the efficiency of liability rules when the probability of accident is not perfectly known. Indeed Chakravarty and Kelsey (2016) finds that a pessimistic injurer will invest more than an optimistic injurer in prevention under (strict) unlimited liability because pessimism causes her to overweight the accident outcome. Besides, Teitelbaum (2007) shows that the injurer will always invest less than what is socially optimal in prevention under (strict) unlimited liability. Our findings are more in line with Mondello (2013) who shows that the injurer can invest either less or more in prevention compared to the first best level of prevention under (strict) unlimited liability.

To illustrate this result, let us consider again nanoscience. The treatment of wastewater relies mostly on a so-called "Five-day biological oxygen demand" test[17] and represents a desirable measurement in wastewater treatment processes. Unfortunately toxic substances and nanoparticles affect bacteria making this technique unsuitable for monitoring and control. Bridgeman et al. (2013) stress that the test has an uncertainty of 15-20% in result accuracy. Therefore, the industry frequently has to over treat to be sure that they comply with the technical standards.

4 Conclusion

This paper delves into the efficiency of strict liability (unlimited and limited) on prevention incentives when risk and ambiguity are considered. We assert that the potential injurer, whose activities cause a risk of environmental disaster can reduce the probability of accident by investing in prevention. We use the Non-Extreme Outcome (NEO) expected utility model (Chateauneuf et al., 2007) to represent the injurer's beliefs and decisions. One novelty of our contribution is that we introduce in the model with ambiguity a belief function built by the injurer depending on her degree of optimism and also on her investment in prevention.

In the risky model, we have demonstrated that limited liability does not always induce low prevention compared to unlimited liability. The bankruptcy threshold is endogenous in our model so that limited liability may induce the injurer to overinvest in prevention compared to the social optimum to save value on the potentially confiscated assets. One should bear in mind, though, that overinvestment in prevention

[17] It is a common and most widely used test to determine at the beginning and end of a five-day period concentration of organic matter in wastewater samples.

does not mean that it is socially welfare improving. Thus, by reducing *ex ante* the probability of accident, she deteriorates the conditions of the *ex post* compensation. The results we obtain contrast the widespread conclusion on underinvestment.

Nevertheless, the central result of the unilateral accident model is that none of the results with risk hold when ambiguity matters. In particular, the injurer tends to overinvest in prevention whenever she believes that she is able to better control for her subjective belief on the accident state than the regulator does with the preliminary probability. This finding is in contrast with the results by Teitelbaum (2007) who shows that the injurer is always investing less in prevention compared to the social optimal level. This result holds for both unlimited and limited liability. Obviously, we are not able to conclude which liability regime might perform better when ambiguity is considered.

From a policy point of view, the relevant question is which liability regime, unlimited or limited, induce the injurer to invest efficiently in prevention measures when ambiguity holds. We are currently not able to give a plausible response to this question. This issue might be further explored with the means of experimental economics. In particular, we need to elicit subject's degree of confidence and attitudes toward ambiguity to test the correlation between both variables. This might give us some relevant information about the sign of $q_{x\alpha}$. Furthermore, experimental economics shall help to go ahead in the analysis of the injurer's decision behavior under limited liability when risk and ambiguity hold. This will be the next step of our research.

Finally, it is worth mentioning that neither Teitelbaum (2007), Chakravarty and Kelsey (2016), Mondello (2013) nor we have analyzed the situation in which the regulator is ambiguous about the objective probability of a potential environmental disaster. It might be worth to model such a situation where both, the regulator and the injurer face a decision in an ambiguous environment. Further research would help to fill this void.

Appendix

Proof of Proposition 2

A partial derivation of (6) with respect to x yields the following first order condition for an interior solution x_{UL}^{amb}

$$1 = -[\delta\pi^{'}(x_{UL}^{amb}) + (1-\delta)q_x(\alpha, x_{UL}^{amb})]l \tag{11}$$

If $q_x(\alpha, .) = 0$, it reduces to $1 = -\delta\pi^{'}(x^S)l$. With $\delta < 1$, comparing this equality with (2)yields Point i).

If $q_x(\alpha, .) < 0$, then the right-hand-side term of (11) may be either lower or higher than $-\pi^{'}(x^S)l$. Precisely, by comparing the social marginal benefit $-\pi^{'}(x^S)l$ obtained with risk with the private marginal benefit under ambiguity $-[\delta\pi^{'}(x_{UL}^{amb}) + (1-\delta)q_x(\alpha, x_{UL}^{amb})]l$, we obtain that:

$$\begin{aligned} x_{UL}^{amb} \lesseqgtr x^S &\Leftrightarrow (1-\delta)\left[\pi^{'}(x^S) - q_x(\alpha, x^S)\right] \lesseqgtr 0 \\ &\Leftrightarrow \left|q_x(\alpha, x^S)\right| \lesseqgtr \left|\pi^{'}(x^S)\right| \end{aligned}$$

This is Point ii). Now write (11) as follows:

$$\frac{\partial W_{amb}^P}{\partial x} = -1 - [\delta\pi^{'}(x_{UL}^{amb}) + (1-\delta)q_x(\alpha, x_{UL}^{amb})]l = 0 \tag{12}$$

Point iii) is obtained thanks to a total differentiation applied to (12) with respect to x and to α. We have:

$$\frac{dx_{UL}^{amb}}{d\alpha} = \frac{l(1-\delta)q_{x\alpha}}{\frac{\partial^2 W_{UL}^{amb}}{\partial x \partial x}}$$

The denominator corresponds to the expression of the second order condition. With $\pi_{xx} > 0$ and $q_{xx} \geq 0$ by assumptions, there are satisfied so that $\frac{\partial W_{UL}^{amb}}{\partial x \partial x} < 0$. The numerator is strictly positive (strictly negative, equal to zero) if and only if $q_{x\alpha} > 0 (< 0, = 0)$. Hence we obtain Point iii). Proposition 2 is demonstrated. ♦

Proof of Proposition 3

Let us subtract the first-order-condition under risk and limited liability (10) from the first-order-condition under ambiguity and limited liability (9), and let us evaluate this difference at point x_{LL}^P. We have

$$[(j_x(\alpha, \delta, x_{LL}^P) - \left|\pi'(x_{LL}^P)\right|)]\widehat{d}_{LL}^P \gtrless j(\alpha, \delta, x_{LL}^P) - (1 - \pi(x_{LL}^P)) \Leftrightarrow x_{LL}^{amb} \gtrless x_{LL}^P \tag{13}$$

The left-hand-side term in (13) is the difference between the expected marginal benefits under risk and under ambiguity evaluated at the private risky optimum x_{LL}^P, while the right-hand-side term is the difference in the expected marginal costs. Let us denote the former as ΔB and the latter as ΔC.

For $\alpha \geq 0.5$ we have, by assumption, $j(\alpha, \delta, 0) - (1 - \pi(0)) > 0$. If $j_x(\alpha, \delta, x) < |\pi'(x)|$ for any x, then we are not able to conclude about the sign of $j(\alpha, \delta, x_{LL}^P) - (1 - \pi(x_{LL}^P))$. For $\alpha < 0.5$ we have, by assumption, $j(\alpha, \delta, 0) - (1 - \pi(0)) < 0$ and the same problem holds if $j_x(\alpha, \delta, x) > |\pi'(x)|$ for any x. Proposition 3 is demonstrated. ♦

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