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Dealing with Major Technological Risks*

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Résumé / Abstract

Cet article d'intérêt général porte sur la gestion des risques d'origine technologique aux conséquences potentiellement catastrophiques. Il s'agit d'un document de synthèse destiné à cerner les problèmes fondamentaux en matière de gestion publique et privée des risques technologiques majeurs. Trois thèmes y sont traités: l'évaluation, la distribution et le contrôle des risques. Les questions se rapportant aux méthodes d'évaluation, à la perception des risques et aux difficultés liées à l'établissement d'un seuil de tolérance sont d'abord passées en revue. La seconde partie du document met en lumière les difficultés que présente le partage optimal du risque entre les différents agents. La responsabilité civile de la firme et de ses partenaires est alors examinée. Les problèmes liés à l'assurance contre ce type de risque sont aussi brièvement décrits. Cet article traite enfin du contrôle des risques en couvrant à la fois les approches préventives et les stratégies d'atténuation des dommages. On y aborde premièrement les instruments de contrôle dont dispose l'État pour réduire les risques. Du côté des firmes, les sujets tels que l'investissement en sécurité, l'erreur humaine, le design organisationnel et la divulgation de l'information sont passés en revue. L'aménagement du territoire et la gestion des urgences sont ensuite abordés de façon succincte dans la dernière partie de l'article.

This article is concerned with the management of major hazards stemming from technology and entailing potentially dreadful consequences. It proposes a brief survey of the main difficulties and policy issues arising both in public and private decision making when dealing with major technological risks. Three themes are considered: risk assessment, risk sharing and risk control. Issues related to evaluation methods, to risk perception and to the acceptable level of risk are first examined. The article then goes on to explore the problem of optimal risk sharing between the different stakeholders. The firm's liability and extended liability to the firm's partners are considered. Insurance issues are also discussed.

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A chapter for the book Principles of Environmental and Resource Economics (2nd edition), Edward Elgar publisher. We wish to thank the editors, Henk Folmer and Landis Gabel, for helpful comments and suggestions on earlier drafts. We also benefitted from several conversations with our colleagues Hélène Denis on risk perception and management, Marcel Boyer, Karine Gobert and Sandrine Spaeter on liability and insurance, and Erwann Michel-Kerjan on catastrophic risks, and with Robert Lapalme of the Ministère de la Sécurité Publique du Québec on the regulation and public management of industrial hazards and risks.

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Lastly, the survey addresses the control of risks both from a prevention and from a damage mitigation point of view. The various instruments available to the State to reduce risks are reviewed and several issues are also raised with respect to the measures firms can take to reduce risks. Investment in safety, human error, organisational design and information disclosure are addressed in this section. The topics of siting and urban planning are analysed as mitigation strategies, and the important aspect of emergency planning ends the survey.

Mots Clés : Sécurité, risques majeurs, évaluation des risques, distribution des risques, contrôle des risques, prévention, atténuation

Keywords: Safety, major risks, risk assessment, risk sharing, risk control, prevention, mitigation

1. Introduction

In an era where technological progress is accelerating, one cannot avoid thinking about the level of risk and uncertainty it entails. For technological progress is ambivalent. On the one hand, it enhances economic growth and the quality of life; it shelters us vis-à-vis natural forces, contributing to the prevention and reduction of latent disasters such as epidemics; and it provides comforting replies to the advocates of pessimistic scenarios based on limited natural resources. On the other hand, it exacerbates the consequences of human error, and past experience also reveals that new industrial processes and products often hide lethal side effects that show up only in the long run.

This chapter is concerned with the assessment, allocation and control of major technological risks. Such risks refer to the probability of occurrence of dreadful outcomes linked to an explosion, a fire, a leakage, or any sudden malfunctioning or misuse of technology (as in Chernobyl, Seveso or Bhopal, for example), as well as to the eventual outbreak of some general disease due to widespread exposure to hazardous industrial substances (like silicone or asbestos, for example). They belong to the category of catastrophic risks, which are characterized by small probabilities of large, collective and irreversible losses [Chichilnisky and Heal (1992)]. They are also man-made and therefore endogenous to human activity [see Smith (1996), chapter 13], unlike natural disasters such as earthquakes or landslides. But they pertain to activities or decisions linked to the production of goods, as opposed to other endogenous catastrophes such as bank runs, financial collapse, war and riots.

Regulation and management practices towards major technological risks are now evolving rapidly. The Environmental Protection Agency, for instance, has set new rules for “risk management planning” only three years ago; these rules are currently being implemented and refined in approximately 66,000 industrial facilities across the United States. This chapter proposes a brief summary of the main difficulties and policy issues which arise when dealing with major technological risks.[1] The presentation unfolds as follows. The next section focuses on risk assessment; it includes topics such as the public's perception of industrial risk and the definition of acceptance thresholds. Section 3 is devoted to risk sharing, or the *ex ante* allocation of liability for damages and financial compensation should a disaster occur. In the fourth section, finally, we cover the subject of risk control. This objective involves two complementary facets which are treated successively: the first one - prevention - tackles what are a priori identified to be the sources of risk, the second one - mitigation - aims instead at designing and implementing contingency plans in order to reduce damages a posteriori. Section 5 contains concluding remarks.

2. Risk Assessment

Risk assessment is the initial step before setting priorities and deciding on cost-effective measures to control risks. To assess major technological risk one must evaluate its two fundamental dimensions: (1) the magnitude of the potential adverse outcomes, and (2) the probabilities attached to them. Risk assessment is not only limited to the analysis of a single worst case scenario. It can provide a global picture and may therefore be presented as a set of probability distributions over a full range of possibilities. The following is an overview of the approaches involved in risk assessment.

2.1 *Qualitative and quantitative assessment methods*

Risk assessment is usually done in two steps. The first one aims at identifying the sources of danger and at describing the extent of potential damages; it is essentially qualitative. For risks associated to engineering system failures, the assessment can rely on sophisticated identification methods such as HAZOP (Hazard and Operability studies) or FMEA (Failure Modes and Effects Analysis).[2] They may use techniques like *fault trees* and *event trees* to spell out the different scenarios. For example, one may want to examine how a discharge of toxic and corrosive slurry into the atmosphere via the stack could happen at a crystallization plant. A fault tree would then allow to discover, working backwards, that the slurry might overflow into the pressure control valve header, that the

[1] Comprehensive surveys are also available. See Lees (1996), or the recent book by Hélène Denis (1998) and the references therein.
[2] For a detailed description of the numerous risk identification and assessment methods, see Lees (1996), volume 1.

operator might fail to take action upon a rising-level signal and not reduce the input, and that all this may have started with the level control valve on a discharge line being shut inadvertently.[3] An event tree would consider the other side of the coin and exhibit the possible consequences of a such an incident, each branch representing a particular outcome.

Estimating the physical effects and extent of damages of a particular release scenario involves the use of consequence or hazard models. Several systems have been developed, many of them computerized, to assess resulting damages from specific incidents such as spills, explosions, fires, toxic releases or other type of emissions. These hazard model systems include the population vulnerability models, the SAFETI computer code, the WHAZAN computer code, and the Yellow Book[4] models. All these make use of dispersion models that trace out the impact zones.

The assessment of latent risks linked to health and environmental hazards focuses on understanding the characteristics and effects on humans of hazardous substances. Uncertainty lies mainly in the extent of damages a substance can cause given a certain level of exposure to it. Evidence of carcinogenicity of dioxins, for instance, is obtained from confronting animal bioassays to high doses and extrapolating from the findings to the situation of humans who are exposed to much smaller doses. Extrapolation involves making assumptions about the shape of the substance-disease relationship. Dose-response models are then used to capture this relationship.[5] They generally give way to two distinct approaches: one that seeks some exposure threshold below which no harmful effects can be detected (the so-called NOAEL or *no-observed-adverse-effect-level*) and another that develops a positive relationship over the whole range.[6] Together with other parameters (nature, duration and spatial extent of exposure, size of the threatened population), this information often leads to norm setting.

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[3] This example is taken from Lees (1996), volume 1.

[4] *Methods for the calculation of the physical effects resulting from release of hazardous material,* developed in the Netherlands by the Committee for the Prevention of Disasters.

[5] For a brief guide on health risk assessment methods, see the referenced document by the American Chemical Society (1998).

[6] For a more detailed analysis of the different dose-response models, their underlying assumptions and the political implications for the regulatory process of toxic substances, see (Harrison and Hoberg, 1994).

At the purely quantitative stage, probabilities are assigned to the different nodes in the chain of events. Probabilities are also associated to the extent of resulting damages. The difficulty is of course to associate probabilities to events for which data does not exist. Hypothesis setting and expert judgement can here play a large role. An example of a comprehensive risk assessment is provided by the Canvey reports. Public investigation leading to this report was triggered by the proposal of United Refineries Ltd to construct an additional refinery on Canvey Island in the UK. One objective was to investigate the overall risks to health and safety arising from any interactions between existing and proposed installations [Health and Safety Executive (1978), (1981)].

The assessment of major technological risk is rarely very precise, however. Inaccuracies in the system's description, lack of confidence in statistical data, the number of judgmental hypothesis being made, the diversity of assessment methods, and the fact that the scope of the analysis might have been limited a priori contribute altogether to set a significant margin of error. Risk assessment results therefore usually include an estimate of the uncertainty attached to them obtained from dispersion values or from sensitivity analysis. This uncertainty can dictate priority setting. For example, one can decide to focus on the better known risks in the name of efficiency and learning, or on the least known risks instead, invoking the precautionary principle.

Another source of controversy in risk assessment is the approach taken to price human and environmental casualties. There are a number of methods that intend to assign a monetary value to risk reduction, as well as to life, health and the environment: hedonic methods applied to the labor market (taking into account wage differentials, for instance), cost-of-illness methods, and contingent methods directly asking the question to the individuals.[7] The credibility of the figures obtained remains questionable, however, not only for ethical reasons, but also because the occurrence of an industrial catastrophe is likely to fuel public anger and to become a political event whose outcome is highly unpredictable.

[7] For a detailed discussion of these methods, see chapters 2 and 3 of this book. See also, Landefeld and Seskin (1982) on the economic value of life, Moatti (1989) on the willingness to pay for safety and Viscusi (1993) on evaluation methods using labor market data.

2.2 *Risk perception*

As mentioned above, the assessment of major technological risks is never exempt from subjectivity. Individual risk perceptions remain an indispensable input, due to lack of data concerning empirical frequencies, or because one usually needs to consider as well the opinions and reactions of less informed stakeholders.

People's biases when dealing with uncertainty are now well documented.[8] For instance, some individuals directly relate the fact that an event or a chain of events seem reasonable to the probability of it happening: the easier it is to visualize, the higher is the assessed subjective probability of occurrence. The ease to identify the victims and the attention given by the media to certain risks are also factors contributing to an overestimation of the risks. This all relates to the so-called "availability heuristic", whereby an event will be judged probable or frequent to the extent that instances of it are easily recalled or imagined. The degree of control one has over the risk is yet another factor likely to affect risk perception. The more control there is, the more underestimated is the actual risk. Moreover, risks assumed voluntarily are not perceived the same way as those which are imposed. An agent willing to move near a toxic waste incinerator may not perceive the risk the same way as one would if the owner of the incinerator chose to settle and work in the neighborhood. Here, the perception of risk may also depend on the existence of benefits associated to risk exposure (eg. lower real estate prices). The presence of such benefits changes the point of reference from which people assess risks and thus may in that way alter their evaluation or perception of the risk. Finally, some people also tend to ignore probabilities that fall below some threshold, although the opposite is also true: in certain occasions, people overvalue small probabilities in proportion with the importance of potential damages and undervalue large probabilities. All these drawbacks make the use of expected utility as a unifying model to encode, aggregate and compare subjective perceptions quite problematic.[9]

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[8] For a survey of risk perception issues and the decision process for low probability events, see Camerer and Kunreuther (1989). See also Slovic (1987) and Viscusi (1992) for models incorporating biases in risk perception, Smith (1992) on the relationship between risk perception, information on risk and behavior under uncertainty, and Lopes (1992) on misconceptions about the public's ability to perceive risks adequately.

[9] For a survey on the topic of expected utility theory and alternative models of choice under uncertainty, see Machina (1987).

The various ways of framing and communicating risk also have an effect on perception. Experimentation shows that different formulations of the same problem give way to opposite attitudes in decision making. Choices framed in terms of number of lives saved entail risk averse behavior or a preference for certainty versus randomness in results; on the other hand, choices expressed in terms of number of lives lost give rise to risk taking behavior or a preference for an uncertain loss over a certain one.[10] In this context, risk communication often has two conflicting goals to meet at once: to warn the people that some immediate actions on their part are required while at the same time reassure them that the whole situation is kept under control. The communicator implicitly seeks to inform the public about the so-called "objective" measure of risk and lead them to update their beliefs.[11] Public trust in risk management institutions is then crucial, for it does have a bearing on the way people perceive risks [Groothuis and Miller (1997)]. Risks are often perceived to be greater than they truly are when institutions are less trustworthy.

2.3 *The "acceptable" level of risk*

Setting an acceptable or tolerable level of risk rarely comes through consensus. A firm will decide upon the risks it considers tolerable based on its legal liability, its assets and revenues, its technological constraints and the availability of insurance coverage. If the risk born by third parties were totally internalized by the firm, the level chosen would in principle be acceptable to all stakeholders. This rarely happens, of course. Employees, environmental groups, as well as the surrounding communities might not see or assess some major technological risk in a similar way. The chosen level of risk, or even the approach used to reach it, might be a source of conflict. Whether the method was some cost-benefit analysis or a benchmarking approach using levels of risk tolerated elsewhere, some stakeholders might point out the limits of science, putting into question the transparency of the process and the objectivity of the experts involved.

[10] See the famous experiment results given in Tversky and Kahneman (1981).

[11] But if communication fails, correcting for public biases will remain contentious as long as people's disagreement is rooted their preferences. For more on this, see Smith (1992).

For large industrial accidents, employees are more likely than external stakeholders to convey their interest further because of their tight relationship with the firm and the bargaining power they have through labor unions. Is this mechanism sufficient to guarantee that the chosen level of risk will seem acceptable to all the parties involved? On the one hand, the higher wages employees receive due to their exposure to risk might raise their tolerance threshold. Furthermore, employees might not know the exact level of risks they are exposed to. Finally, some selection bias in recruiting and the effect of training might make to pool of employees constitute a bad representation of the exposed population.

When a new firm is about to settle nearby, surrounding communities and local residents often engage in lobbying. In this case, public hearings in the process of environmental impact assessment certainly provide for more transparency and for the revelation of preferences. In most cases, however, the plant and its accompanying risks are already present in the neighborhood. This *fait accompli* leaves little room for dialogue and compromise. Communities are thus generally subject to negative externalities. They have little negotiating power, apart from the threat of legal suits which, as we will see, also present some difficulties. Furthermore, they are often ill-informed and unable to reach a proper assessment of the risks.

Setting an acceptable level of risk is thus inevitably a political process, which may be guided by economic tools [Moatti (1989)]. Economic efficiency and cost effectiveness prescribe an optimal level where the marginal cost to reduce risk is equal to the marginal benefit of having a more secure environment. This approach was supported, for instance, by the International Commission of Radiological Protection and is embedded in popular criteria such as ALARA (As Low As Reasonably Achievable) or ALARP (As Low As Reasonably Practicable). In a wider multi-criteria approach, however, other factors can be given more weight and may prevail. Society might want to give priority to employment or regional development, for example, and the acceptable level of risk will then be that minimal level compatible with technological or financial objectives. In other circumstances, Society might instead choose a certain threshold of risk, without being overly concerned with the economic or opportunity costs that the attainment of such a level implies. Most practical approaches are of course combinations of the above. In addition to some technically and economically feasible lower bound, they usually prescribe some upper level above which a risk is considered intolerable and must be reduced. Risks that fall between the two boundaries are deemed acceptable only if all practical and reasonable measures have been taken; some calculation towards an optimal solution is thereby asked for. As an illustration, the Canadian Council for Major Industrial Accident (CCMIA) considers, for instance, that with a probability of damages above 10^{-4} a risk is unacceptable, but with a probability below 10^{-6} it is. Between those two thresholds, acceptability depends on the use of land and on the feasibility of emergency measures.

A complement to the above is to decompose the chosen risk level further into specific safety goals. After satisfying explicit rules and regulations, a firm may set some threshold for the probability of a severe accident, and then formulate distinct objectives concerning what is the acceptable probability of casualty for an individual worker (for instance 10^{-3}) and for someone from the public (say 10^{-5}). This procedure is often followed in Europe, particularly in Holland [Paté-Cornell (1994)].

Finally, the precautionary principle provides another guiding tool to establish the proper level of risk [Gollier, Julien and Treich (1999)]. In its best known formulation this principle says that one should not await greater scientific certainty before adopting protective measures. The precautionary principle thus embodies the fact that when risks are not well known, preserving flexibility of action – or the possibility of adjusting or relaxing stringent standards as new information becomes available – has a value that must be taken into account when assessing the benefits of reducing the risk. The same type of reasoning holds when damages are totally irreversible. The precautionary principle currently lies at the foundation of recent European regulations concerning global warming and genetically-modified cereals.

3. Risk sharing

Sharing technological risks means to allocate *a priori* amongst the agents the financial liability of the potential damages. Who will be responsible for the restoration of the environment and for the compensation of victims? The firm and its insurers? The victims' insurers? Other partners of the firm? The government? The allocation of liability by law and by contract between the different agents is essential for many reasons. First, sharing the risk allows for the sustainability of different activities that would otherwise be abandoned. Most firms could not support alone the burden of liability without running an excessive risk of going bankrupt. They must therefore share the risk with agents – insurance companies in most cases – willing to add these risks to their portfolio of diversified risks. Risk sharing also contributes to make other agents who are benefiting from the risky activities aware of their responsibilities and accountable for their decisions. By making the surrounding communities or consumers support some fraction of the damages (denying them a total compensation), and by making the partners of the firm - business or financial ones - support some of the risks, one might increase prevention and mitigation efforts, thereby reducing everyone's exposure. Of course, optimal risk sharing needs to take into account the respective interests and degree of risk aversion of all stakeholders, and the means they have to supervise and change the prevailing level of risks.

3.1 *Civil liability*

The first risk sharing instrument is the degree of civil liability of the firm and of its partners.[12] It is given by tort law and by statutory extensions or limitations of this liability. From these rules, shareholders, lenders, insurers and other business partners make decisions that will have an impact on the prevailing level of risk. The State has two objectives in mind when establishing civil liability rules. First it wants to spread risk so that social cost is internalized, negligence is deterred, and the risk is brought to an acceptable level. Second, the legislator wants eventual innocent victims to be fairly compensated whenever possible.

The general civil liability rule imposes on individuals or firms the duty to restore or compensate for damages caused by their negligence. In principle, such a rule gives

[12] Pathbreaking work on this topic was accomplished by Calabresi (1970). Here we distinguish civil liability rules or tort law, whereby victims may claim compensation for the damages suffered, from penal or statutory liability rules where corporations, directors or officers are exposed to sanctions (fines or imprisonment, but not compensation) if proven guilty of an offence. For a discussion on penal liability rules, see chapter 15 of this book.

incentives to the firm to control its risks tightly and to prevent any damages to third parties, without the need of legislation on particular control measures. In practice, however, there are several well-known obstacles to the application of this general rule in the context of major technological risks.

First, the burden of proof can easily become overwhelming for any plaintiff. Negligence can be difficult to establish in a context of innovation, for instance, or where industrial standards of safety are yet to be defined or are too difficult to verify. The legislator may then decide to enact presumptions of negligence and when certain conditions are met, the onus of proof will be on the firm to show that it took the reasonable care expected in the circumstances and adhered to established safety standards. To this end, conformity to ISO standards like the 14000 series on environmental management, the upcoming 18000 ones for health and safety in the work place, or the *Responsible Care* guidelines for the chemical industry may provide a successful defense. The legislator can also establish a strict liability rule where the plaintiff only has to prove a damage as well as the causal link with the firm's activities, but not negligence on the firm's part. In that case, the firm will not defend itself by simply proving reasonable care and the respect of all recognized standards: only an *act of God* - the fact that the damage was totally unforeseeable or the fault of a third party (or of the victim) - would exonerate a defendant. In the case of strict liability, victims are more likely to be fully compensated than under a negligence rule. Regimes of strict liability rules were adopted in the United States notably with the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA). The Council of Europe has also adopted such a regime in 1993 in the Convention on Civil Liability for Damages Resulting from Activities Dangerous to the Environment (ETS No. 150). This type of regime may lead, however, to excessive prevention, or push certain firms to simply exit the industry. If the firm bears all the risk of an accident and cannot show that it was caused by a random factor, it will become much more conservative, and the accrued precaution is likely to be reflected in price increases and a loss in competition if firms leave [Shavell (1979), Manning (1994)]. Finally, the proof of damage itself may not always be easily made. This is especially true for latent diseases. Showing a causal link between an activity and some occurring damage may be difficult when the damage could be attributed to a combination of many factors such as the climate or the victims' health. The success of the plaintiff and the effectiveness of the liability rule will depend on the conclusiveness of the proof that is required from the plaintiff. Chapter 15 provides a more in depth analysis of the efficiency of different liability rules for promoting safety behavior and victim compensation.

Transaction costs can also jeopardize both the incentive mechanism and the compensation objectives. Litigation costs – including time and expertise costs – preclude the victims from being totally compensated and discourage some proper use of the system. The dispersion of damages among a large group of victims can present some further difficulties when each person is affected in a small fashion and nobody alone has enough incentive to bring the case to court. Class action suits may then alleviate this problem.

Whether the goals of safety and full compensation can always be met by a single liability rule is therefore unlikely.[13] But perhaps the most critical aspect of liability rules in the case of major technological risks is the fact that the liability of a corporation is limited to its assets. When damages are much larger than the assets of the company, incentives for risk reduction are more limited: to the eyes of the firm a large-scale catastrophe is the same thing as one that just makes it go bankrupt. The level of prevention will therefore not differ past a certain point. Some existing solutions to this problem are presented in the next subsections.

3.2 *Extended liability to the firm's partners*

The firm who holds the risk-inducing technology rarely constitutes the only node in the production chain. Financial institutions provide funds to support the firm's activities, and other commercial partners either consume the firm's hazardous products or participate in the production process as input providers.

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[13] For the necessity of a combination of instruments depending on the characteristics of the risks, see Katzman (1987) and Segerson (1992). To illustrate further, consider torts where several several injurers may have contributed to a single damage. A joint and several liability regime will foster the compensation goal by permitting the plaintiff to sue all or any of the injurers. But the cost of poor practice is then spread amongst many firms who then have lower incentives, individually, to take good care.

A firm may be tempted to outsource risky activities and make subcontractors bare the responsibilities associated to them. In this case, potential subcontractors will naturally demand a risk premium and the size of that premium will determine in part whether the activity will be subcontracted or not [as exemplified, for instance, in a recent study by Aubert, Patry and Rivard (1998)]. For activities occurring in a highly competitive market, like transportation, outsourcing is all the more appealing since the premium that can be extracted is limited by the market structure. But transferring risky activities to competitive subcontractors may result in lesser effort devoted to safety. Subcontractors cannot generally manage these types of risks nor insure themselves as easily as larger firms. Furthermore, smaller contractors may be more reckless since they have much less to lose. This may lead them to take less precautions and to underinvest in their processes in order to shelter their assets from major technological risks, for in the event of an accident, they may always benefit from the protection of bankruptcy laws.

One way out of this is to make several nodes in the production chain (subcontrators and subcontractees, lenders and debtors) jointly and severally liable in case of a major industrial accident. One hopes thereby to facilitate victims' compensation by going into the "deeper pockets", insuring that the latter do not let others with "shallow pockets" run unreasonable risks. The presumption is also that the involved external parties will put pressure on the firm to make sufficient investments in safety. The courts will trace the participation of firms linked to the risky activities either by the fact that they possess critical information concerning safety, or by the fact that they are the owner, operator or manufacturer of the processes or products at stake.

The economic downside of an extended liability regime, however, is that the targeted firm might change its pattern of transactions or expose less capital to liability when it cannot invest in safety nor control the risk. [Boyd and Ingberman (1997)] For instance, toxic waste producers may be held liable for damages due to a leak in the landfill operated by another firm in which their waste is disposed of. By wanting to limit the wealth they are exposing to liability, targeted waste producers, especially smaller ones, may exhibit distorted capital investment and output choices. Furthermore, this regime might encourage contractual relations or affiliation between firms with similar degrees of solvency or safety standards: deep-pocketed firms will avoid contracts or affiliations with shallow-pocketed firms, even when it is not socially optimal, and small firms will get together without putting due care on the risk they generate.[14] So while extended liability may improve social cost internalization and deterrence, it may not necessarily improve welfare and a tradeoff must be made.

Legislation like CERCLA in the United States and other regulations on the allocation of clean up costs for contaminated sites are used to extend liability to lenders. The decision power of secured creditors in the firm management or the fact that they become owner of certain assets when the firm is in default can lead to their liability. Here again, extended liability may have downsides. It may affect the availability of credit, the cost of capital and the level of investment. Research results show among other things the importance of the information structure and of asymmetric information phenomena such as *moral hazard* - not observing the firm's efforts on prevention and mitigation – and *adverse selection* - not knowing the firm's initial risk profile - on the optimal extended liability rule. They suggest that lender's liability be only partial.[15]

3.3 *Insurance*

Firms facing major technological risks will seek to insure themselves whenever such insurance exists at a reasonable cost. Demand for insurance against liability claims by industrial firms results in part from risk aversion on the part of concerned firms and their shareholders or lenders; it may also be required by the law. The Convention on Civil Liability adopted by the Council of Europe requires that firms have a financial security scheme to cover liability. This scheme may take the form of an insurance contract or other financial arrangements among an industrial pool for example.[16] In the United States, the same is required from facilities that produce or handle hazardous chemicals by the

[14] Affiliation between firms is recognized when several contractors or clients do business with a common producer.

[15] For a survey on lender's liability, see Boyer and Laffont (1996). Gobert and Poitevin (1997) and Pitchford (1995) also present different approaches to derive the lender's optimal liability rule. For a discussion of lender's liability within the general corporate landscape, see Boyer and Sinclair-Desgagné (1999). For empirical evidence of the effect of such legislation on the cost of capital, see Garber and Hammitt (1998).

[16] See section 12 of the Convention on Civil Liability for damages resulting from activities dangerous to the environment (ETS No. 150).

Resource Conservation and Recovery Act. Compulsory liability insurance enhances the compensation of victims who would otherwise face a bankrupt firm.

Other benefits can be derived from insurance with respect to major technological risks. By design, the terms of an insurance policy, namely the premium, the extent of coverage, restrictions, exclusions and deductibles, should separate and deal with the various sizes and types of risks involved. Insurance contracts then become a mechanism that provides incentives to reduce risks. The insurer thereby takes the role of a surrogate regulator. The case of industrial boilers is a good illustration of the role insurers can play in risk reduction [see Paté-Cornell (1996), Er et al. (1998)].

For most major technological risks, however, insurance is not readily available, so insurers cannot fulfill a role in risk sharing and reduction. Technological risks that are too uncertain for a firm to bear may also be too uncertain for an insurance company that typically shows ambiguity aversion [Kunreuther et al. (1995)]. Lack of actuarial data and their public good nature, dramatic consequences that can amount to enormous costs, the uncertain duration of adverse effects or of the latency period, and the fact that liability rules can change over time can deter insurers from entering the market. Moreover, the increasing complexity of technology, which makes the causal relationship between safety measures and risk reduction difficult to grasp, tends to exacerbate both the classical problems of adverse selection and moral hazard.

Under adverse selection, when insurance companies cannot assess precisely the respective risk of their potential clients before agreeing on the terms of a policy, insurance becomes less efficient as a means to redistribute risk [Borch (1990)]. An average rate coupled with cross subsidies between low and high risks is no longer sustainable because it is not attractive to low-risk agents. Different policy packages are then offered – high premium/large coverage and low premium/partial coverage – so agents will implicitly reveal their risk profile by the choice they make. The most likely outcome is then under-insurance of firms who generate lower risks, since only those firms will choose a partial insurance contract. Hence when adverse selection is too severe, as may be the case for major risks, there can actually be no insurance available: no package will be profitable at current insurance premiums, and raising premiums would only attract the worst risks, reducing profits further.

Moral hazard, or the possibility that the firm, once insured, takes less prevention measures, will also reduce the available coverage [Shavell (1979)]. Unless the level of safety and prevention is perfectly observable by the insurance company, the insured agent has less incentive to be prudent, once insured, and is therefore more likely to cause harm. In this case the only way to provide some incentive for prevention and damage mitigation is to offer an incomplete coverage (or a large deductible), thereby making the insured firm bear some of the risk. There is thus a tradeoff between optimal risk sharing and incentives to prevention and mitigation. Experience rating - when subsequent premiums depend on the track record of the firms – is sometimes invoked to alleviate this tradeoff. It is not, however, a system that insurance companies can rely on for major technological risks, since data in this case is so rare. An alternative route is ex post supervision with coverage and premium depending upon the observed prevention and mitigation levels. Such inquiries, however, are often very costly.

Finally, insurance availability is also limited in some areas due to the correlation of risks. If the risks of the whole pool of insured agents are not statistically independent, the probability increases for an insurance company that it may have to pay out indemnities all at once; some insurers might then find this too large a risk to bear. This may be the case for widespread substances that prove to be hazardous at the same point in time (like asbestos), triggering massive toxic torts. The year 2000 computer bug is another example of the kind of risk uninsurable for high correlation reasons. Another source of correlation can come from changes in liability rules that make all insured agents liable at once.[17]

Insurability of major technological risks is thus problematic. However, it holds an important key to proper internalization of those risks: insurance contracts can provide incentives for risk reduction by aligning their terms with good risk control measures. One important improvement in the management of major technological risks would therefore be better techniques to monitor and appraise initiatives in risk control. For this, one needs some means of references for recognizing the application of reliable measures. Er et al. (1998) propose third-party inspection to improve risk estimate and thereby enhance the role insurance can play in risk reduction and risk sharing. Risk retention groups - where insurance funds are held by industrial pools of similar policyholders - may also provide a solution. These groups are in a better position to monitor managerial performance than an external insurance company and may do it at lower costs.[18]

4. Risk control

Risk control measures include self-protection, i.e. activities affecting the probability of a loss, and self-insurance, i.e. activities aimed at lowering the loss itself when it occurs.[19] The firm's or the risk maker's problem is to choose an optimal combination of the two approaches to risk control. Boyer and Dionne (1983) have shown that a risk-averse agent would prefer self-insurance to self-protection even when they both reduce the expected loss to the same extent and at the same cost. Intuitively, self-insurance is more efficient because it increases the wealth in the bad state where the marginal utility of income is higher. However, in the context of major technological risks, the irreversibility of losses often makes both types of activities indispensable and equally important, if not mandatory. This section reviews the literature on both subjects, starting with the former. To be consistent with current literature, self-protection is called prevention, while self-insurance refers to mitigation efforts.

4.1 *Prevention*

Preventive measures involve both public and private means of intervention. Some of the possible strategies will now be discussed.

4.1.1 *Public measures*

State intervention in the field of safety with respect to major technological risks is rather extensive.[20] It is justified on the grounds of classical market imperfections such as imperfect information and, of course, negative externalities. Control of activities

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[17] For an analysis of liability insurance and catastrophic environmental risk, see Katzman (1987).
[18] For other solutions to insurability problems, see *Contributions to Insurance Economics* (1992) Ed. Dionne, G. Boston : Kluwer Academic Press.
[19] See Ehrlich and Becker (1972).
[20] For a good overview of the role the government can play in the management of environmental risks and an analysis of the efficiency of different policy instruments, see Segerson (1992).

generating risks through command and control regulation, legal liability rules or economic incentive instruments such as Pigouvian taxes, tradable permits or refundable deposits all offer advantages and drawbacks. While economic instruments provide more room for efficiency and the implementation of cost effective measures, they are not easily applicable to actions that are (1) discrete and (2) difficult to monitor as is often the case for actions leading to major accidents. Legal liability rules, like economic instruments, also provide incentive to reduce risk as well as securing some compensation for victims should the damage occur. Furthermore, they do not require that the firm's behavior be monitored. Liability rules have nonetheless their limitations as we saw. They are thus invariably complemented with safety regulation. Defining safety standards and obligations, together with fines and other sanctions for noncompliance, remains in fact the most common approach to regulating hazardous processes and products. The following is a list of existing command-and-control legislations designed to reduce risks.

Table 1 Command-and-control legislation to reduce risk
Occupational safety and health legislation
Public health legislation (food and drugs, etc)
Environmental legislation, itself very vast : air, water, ground quality, impact assessment, etc.
Flammable, explosive and fire legislation
Toxic substances legislation
Labelling legislation
Storage legislation
Waste disposal legislation
Transportation legislation
Consumer product safety legislation
Ports and waterway safety legislation
Nuclear installations legislation
Other energy specific legislation

The difficulty with command-and-control intervention on the other hand is that the legislator must be omniscient. She must know everything about technology and about the performance of different risk reduction measures. This knowledge acquisition may turn out to be very costly. Furthermore, the government must carry inspections to insure that legislation is enforced. The actions likely to lead to accidents must therefore be observable at a reasonable cost in order to be efficiently regulated.[21] Command and control regulation is nevertheless often preferred, for it addresses problems more directly than economic incentives generally do.

Banning some products or processes is another, albeit radical, avenue that is often taken. The fact that society in this case loses some benefits it would otherwise reap from technology can be justified by invoking the precautionary principle, or because the irreversible nature of the damages (say the potential losses of hundreds of lives) forbids any cost-benefit tradeoff, or finally because it is not in the firm's interest to find out at its own costs the true risks involved [Shavell (1993)].

State intervention to prevent damage can also take the form of subsidy for the development of safer technology. It can actually be more efficient to have particular agreements between the government and the firm in order to meet the goals of regulation. This is the case, for instance, when enhanced safety requires the development of new technology or when research results have a public good nature. In this case, the government wants to both control behavior and stimulate innovation, two goals that can be more easily achieved by a kind of contract that sets certain standards on the one hand and that subsidizes part of the innovation on the other [Carraro and Siniscalco (1996)].

Many official reports and inquiry have brought up the need for "goal setting" type of regulation instead of the standard-setting type.[22] With goal-setting regulation, operators must demonstrate safe design and operation to the regulator rather than mere compliance with pre-specified technologies and checklists. In keeping with this, both the United States and the European Union have adopted major hazard legislation to control these risks. In Europe, in the aftermath of the Seveso disaster in Italy where an accidental

[21] See Shavell (1984) for the characteristics risks must show in order for the regulatory approach to be appropriate.
[22] The Report after Three Mile Island and the Piper Alpha Report both insisted on this aspect.

release of dioxin shook the whole continent, the European Council adopted the 1982 Seveso Directive, which was reinforced in 1988 and 1996. It essentially requires that there be an obligation for firms to adopt safety measures and emergency plans, and that this information be made available to the public. Similarly, the U.S. Environmental Protection Agency has recently strengthened the control of risks by developing performance-based (or goal setting) regulations also aimed at preventing and mitigating major chemical accidental releases. These new rules are commonly referred to as the Risk Management Planning requirements or RMP.[23] RMP imposes on firms producing or handling certain chemical substances the obligation to conduct an offsite consequence analysis assessing the worst-case scenario and to develop and implement risk management programs including emergency plans. All this information must be submitted thereafter to a central location and be made available to the local authorities and the public. One goal here is to appeal to market mechanisms to induce risk reduction, in particular to capital markets believed to be sensitive to this kind of information [Kleidorfer and Orts (1998) and Lanoie et al. (1998)].

4.1.2 *Private measures*

Once a firm meets safety standards imposed by law and regulation, it may still seek to decrease its residual risk. Actions firms can take to control the source of risks and reduce the probability of damages include the adoption of inherently safer technology and of technical safety features (additional safety valves, detection devices, etc.), and the reduction of hazardous material inventories. Increased emphasis has also recently been put on management systems, such as specific training to promote workers' reflexes and awareness concerning safety, task division and clear definition of responsibilities, information and control systems keeping track of interventions, and audit schemes to detect lacunae and suggest remedies.[24]

[23] EPA rules on Chemical Accident Prevention and Risk Management Planning were adopted in 1996, pursuing the Clean Air Act amendments of 1990, section 112 (r). Firms have until June 1999 to submit their plan.

[24] See also Chapter 10 for a discussion of these issues within the framework of operations strategy.

Table 2 gives an overview of the typical elements of process safety management.[25]

Table 2 – Elements of process safety management
Review and documentation of the plant's chemicals, processes, and equipment;
Detailed process hazard analysis to identify hazards, assess the likelihood of accidental releases, and evaluate the consequences of such releases;
Development of standard operating procedures;
Training of employees on procedures;
Implementation of a preventive maintenance program;
Management of changes in operation that may have an impact on the safety of the system;
Reviews before initial start-up of a process and before start-up following a modification of a process;
Investigation and documentation of accidents;
Periodic safety audits to ensure that procedures and practices are being followed.

When these elements are implemented and emergency plans (discussed later) are put in place, however, several questions remain to be answered. What is the best strategy, reducing the risk further or insuring it as it is? What is the optimal level of investment in safety? Is the so-called "human error" entirely controlled? In the next subsection we relate these to the observations of several studies and expand on the importance of organizational means.

The safety versus productive investment

All members of the firm face this apparent trade-off, from the bottom hierarchical levels to intermediate managers up to the board of directors. High-ranked executives must decide on the financial resources that will be devoted respectively to safety and market

[25] These elements are part of the OSHA Process Safety Management Standard. The Center for Chemical Process Safety, established as a Directorate of the American Institute of Chemical Engineers following the Bophal disaster, proposes similar elements in its safety process management guide.

research, whereas the foreman must decide whether or not he should spend an extra day double-checking safety procedures instead of spending time on more productive (and often more visible) activities.

The safety budget decision – upgrading older equipment, hiring extra people, improving maintenance, etc. – should in principle be related to the marginal productivity of such investment and the marginal productivity of other inputs. How does further investment in safety translates into reduced liability, lower insurance premium, better access to capital, stronger partnerships, etc.? Measuring this however, poses problems, for it is difficult to establish the effects of some prevention measures (especially organizational ones) on low probability levels. When dealing with recurrent workplace accidents with relatively smaller consequences (albeit very significant, when workers die or when a whole plant is shut down for several days), the marginal productivity of safety investments might be easier to measure. This is, however, not the case for low probability events with very large consequences. It is therefore not surprising that safety budgets are often dictated by safety regulation, industrial standards or insurance companies. Empirical studies actually notice an overemphasis on insurance as opposed to actual risk factors and the lack of communication and coordination between the financial division of the firm, that usually deals with insurance matters, and the production staff, who generally take care of safety [see Paté-Cornell (1996)]. Furthermore, it has been observed that firms tend to focus on short term production goals as opposed to long term safety issues. This is especially true for companies experiencing financial difficulties. It was the case for the Union Carbide plant at Bhopal, although other factors also contributed to the disaster [Lees (1996)].

Human error

Be it in design, in construction, or during operation and maintenance, human error is often seen as the culprit after a major industrial accident occurs. And for good reasons: in a study of marine systems such as offshore platforms, for instance, it was found that only 5 % of the failure probability could be truly attributed to random factors or "bad luck," 40% to design errors and the rest to operation errors [Paté-Cornell (1990)]. Human errors can be classified under the following headings: slips and lapses, mistakes, misperceptions, mistaken priorities and straightforward violations. Causes of human errors can be some external events or distractions, the operator's inability or poor training, excessive demands and pressure being put on personnel, and biased incentives. Several observers have noticed that the allocation of resources between technical and organizational or managerial measures are not well balanced, and that if more attention were devoted to management, then the occurrence of human errors might diminish [Paté-Cornell (1996); Warner et al. (1992)]**.** But firms typically prefer to add physical redundancy or to use stronger materials rather than rely on better training, hire more competent managers and operators, or have external reviews (audits) of technological design. The report following the Three Mile Island incident actually pointed out this bias in the allocation of resources.

Organizational measures

Poor involvement of high executives in risk management is often mentioned as a factor contributing to higher levels of risk. It was one of the main criticism in a report leading to the shut down of seven nuclear reactors in Canada in 1997. It is also one of the lessons learned from the Seveso accident where the directors of the corporation ultimately responsible were unfamiliar with the hazards. More involvement of high ranked officials in routine risk management should allow for a stronger control of intermediate management decisions. On the other hand, by limiting the decision power on issues that intermediate managers often master best, the firm might lose some opportunities that do not necessarily compromise safety. Furthermore, better monitoring by higher hierarchical level will be futile if the actions of employees or lower ranked managers are not readily observable or if one would need to be close to them at all time to detect problems and to prevent them.

Other mistaken organisational arrangements can contribute to increase risk levels. For example, when the distribution of tasks is such that the responsibility for risk management is separated for highly dependent subsystems, the lack of coordination can have unforeseen repercussions. The explosion of the Challenger space shuttle and the

Eurotunnel 1995 fire are illustrations of this point. Task design, distribution and remuneration can lead to consistent biases away from safety activities. Different arrangements are then needed to realign employees' incentives with the firm's safety goals. It might be worthwhile, for instance, to delegate different maintenance activities to different divisions when those activities cannot be monitored equally well. Otherwise, a division in charge of both tasks would be tempted to allocate more effort to the more easily monitored ones, in order to signal diligent work, and neglect the other one [Holmstrom and Milgrom (1991)]. When the tasks cannot be easily separated, a special audit and remuneration scheme may not only promote an efficient allocation of effort in both safety and production but also induce synergies between otherwise substitutable tasks [Sinclair-Desgagné (1999)]. It might also be safer to avoid letting a single division decide on the adoption of a new technology when the choice involves technologies characterized by different risk levels and different maintenance requirements. If the division is in charge of maintenance, safety could be neglected and the ultimate decision would not be in the best interest of the firm [Hirao (1993); Itoh (1994); Vafai (1998)].

Information disclosure

Efficiency and learning about loss control measures require that information concerning near-misses, alerts and other deficiencies be disclosed instead of remaining in a private circle. Information demonstrating reliability of the engineering system and of the risk management system should also be disclosed, as it promotes the reputation of the firm and may enhance its value. However, the implementation of any system aimed at revealing key information is likely to face fierce resistance. The fear of reprisal naturally leads employees to dissimulate their own problems, mistakes and errors. But loss control measures cannot improve without their collaboration on this. Hence, several experts favor a forgiving approach rather than a carrot-and-stick one with respect to individual performance in risk management; they believe this would encourage information revelation [Warner et al. (1992)]. It is certainly necessary to take into account all market features that can have a direct impact on the firm's value and the executive's career prospects in order to find ways by which executives would voluntarily submit the firm to safety audits or any system that discloses information.

4.2 *Mitigation*

Containing the scale of adverse events through ex ante and ex post mitigation measures is the other route that leads to risk reduction. It can be a very effective strategy, especially when there is a lot of uncertainty about the probabilities of failures or about some particular effects. The extent of damages in a given industrial accident is a function of two essential elements: (1) the quantity of people and the value of resources exposed to the risk, and (2) the effectiveness of emergency intervention. These are under the partial control of public authorities and the firm through complementary means that are presented below.

Siting and urban planning

Zoning regulation is certainly one of the oldest and most obvious form of risk reduction. By splitting the territory and isolating hazardous plants, public exposure to risk is diminished. Environmental assessment procedures may also require proper risk analysis that defines a transition zone, helping thereby to determine a location minimizing the potential damages. The solution is not always easy to implement, however. First, firms may be reluctant to locate at a distance that raises their transportation costs or affects the availability of inputs. Linking risk performance and zoning is used more and more frequently to circumvent this problem; it allows more flexibility in land use as long as the firm controls the risk with other measures. This of course defeats the purpose of using mitigation measures to further reduce the risk. This alternative is also more costly in terms of monitoring and emergency planning and may shift the cost from the firm and its particular clients to the local community. Secondly, zoning regulation typically categorizes industries into different types – light, heavy or general – and locates them accordingly. These categories based on historical data can rapidly become outdated due to innovations in products and processes.

More critically, relatively few local communities take or have taken into account major technological risks in their zoning decisions. Their analyses are usually confined to common nuisance like noise and odors. Another difficulty comes from the strong lobby of developers who do not see a problem in impeding on transition zones that should normally be prohibited for residential purposes. This was actually one of the main problems at Seveso; it was also particularly acute in Mexico City when the petrochemical terminal of PEMEX exploded, as well as in Bhopal where shanty towns extended up to the plant's boundary. Local authorities in financial difficulties are less likely to resist this pressure. Finally, grouping several hazardous plants within one area may entail another tradeoff: the population might be less exposed to each risk taken separately, but the likelihood of a domino effect and much larger damages can rise with the geographic concentration of risks.

In 1992, the OECD set some guiding principles for zoning decisions: there should be general zoning criteria as well as a case by case assessment for any new industries and for any new development near hazardous installations. It is, however, recognized that risk assessment is still largely absent from land use planning and zoning regulation, a problem that the latest amendments to the Seveso Directive have sought to address. One reason explaining this problem is the lack of clear and accepted guidelines on both the methodology for risk assessment and on the definition of an acceptable level of risk [Canadian Council for Major Industrial Accidents (1995)].

Emergency planning

The other approach to damage mitigation consists in preparing in advance the interventions of the different parties in case of a disaster in order to prevent further escalation of the original incident. In a study done by the Reactor Safety Study of the Atomic Energy Commission, it was estimated that for a particular scenario early fatalities would be reduced from 6200 to 350 if there was effective evacuation [Atomic Energy Commission (1975)]**.** However, although emergency planning is usually required by regulations on hazardous substances and processes, technical and organizational uncertainty in the firm and the lack of proper contingency plans are factors that often prevent damages from being properly contained.

The essential elements of an emergency plan are the control systems, personnel with specified responsibilities, communication scenarios, clear rules and procedures, and coordination/cooperation between various external and internal services. Communication is of particular importance in the very first stages of a crisis since it is at that time that key interventions are made. Nevertheless, delays in reaction and in communication are often observed. Typically, each level waits until the situation is locally out of control before alerting other divisions all the way to public authorities and the population. The level of preparedness and coordination of each party involved – the firm, the public security teams, and the population – is thus crucial and will determine to a large extent the scale of damages.

Of course, it is not sufficient that emergency plans be thoroughly designed. Actually, the main lesson from the past is that these plans should be kept simple and flexible, and be capable of being scaled up or down according to circumstances [Lees (1996), volume 2]. They must also be put to trial and reassessed regularly. This requires time and resources since the operations will often be interrupted. It also requires that the firm accepts some transparency vis-à-vis its workers and the surrounding communities. Unless a culture of safety is well embedded in the organization and there is prior coordination with public security and with the community, damages are bound to be large. This culture largely bears on a voluntary basis, but legislation like the new RMP rules in the US reinforcing the Emergency Planning and Community Right to Know Act and the Seveso Directive in Europe certainly contribute to tighter relationship and coherence between stakeholders. Both of these regimes require that firms dealing with hazardous substances develop emergency response programs including procedures for informing the public and coordinating with the local agencies responsible for emergency intervention.

5. Conclusion

Regulations and management principles toward major technological risks are now evolving rapidly, following the pace of innovation. This chapter summarized the main traditional facets of dealing with major technological risks: assessment, insurance, prevention and mitigation. It is probable that each of those aspects will change significantly over the next decades. Changes will be triggered by the outcomes of the millenium bug and the consequent realization by the public of the current overreliance on larger and larger computer networks, and also by the proliferation of new drugs, products and livestock born from genetic manipulations. We believe, however, that the categories and tradeoffs emphasized above [following Warner (1992)] - quantitative vs. qualitative assessments, preventive vs. mitigating expenses, no-fault vs. carrot-and-stick approaches, narrow vs. broad stakeholders involvement – are inescapable and will therefore prevail. It is the answers to those tradeoffs that will adjust, according to the evolution of society and of technology.

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