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Risk aversion and the external cost of a nuclear accident

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The external costs of fuel cycles used in the production of electricity can be defined as those imposed on society and the environment, that are not accounted for by the producers and consumers of energy. Within the evaluation of the external cost of the nuclear fuel cycle, the estimation of the external cost of a severe nuclear accident is one of the major topics to be addressed. For this purpose, the usual approach consists of calculating the expected value of the cost of various accident scenarios. The main criticism of this approach is that there is a discrepancy between the social acceptability of the risk and the average monetary value required for paying compensation to each individual affected by the accident. This paper proposes a methodology, based on the expected utility approach, for integrating risk aversion into the evaluation of the cost of a nuclear accident, as well as a numerical application based on French data.

Although a wide range of values have been published for the coefficient of relative risk aversion, it seems reasonable to adopt a value of 2 for the specific case of nuclear accidents. This leads to an estimated multiplying factor of approximately 20, to be applied to the expected external cost of a nuclear accident corresponding to a release of about 1% of the core. In this case, the external cost of the nuclear accident is estimated to be 0·046 mEuro kWh^{-1}. This represents about 50% of the total external cost of the nuclear fuel cycle without accident (estimated at 0·1 mEuro kWh^{-1} with a 3% annual discount rate).

Keywords: expected utility, external costs, nuclear accident, risk aversion.

Introduction

In the context of the Joule Programme of the European Commission, the ExternE project was implemented in 1991 to assess the external costs of various fuel cycles used in the production of electricity. These costs are those imposed on society and environment that are not accounted for by the producers and consumers of energy, that is those not included in the market price. The main objectives of the ExternE project are to develop a unified methodology for quantifying the various external costs associated with different fuel cycles, to allow an international comparison and the integration of external costs in overall economy–energy–environment models (Valette, 1995).

The general methodology applied in this project is called the 'impact pathway analysis', which is based on a sequence of evaluations from source terms to the potential effects on mankind and the environment, and includes a monetary valuation. The approach adopted for the monetary valuation takes into account the revealed preferences of individuals, and especially their willingness to pay (WTP) for improved environmental or health quality, or their willingness to accept (WTA) environmental or health damage.

As far as the nuclear fuel cycle is concerned (Dreicer *et al.*, 1995), a first set of questions arises from the risk assessment, especially when potential reactor accidents of different severity levels have to be considered with their associated probabilities and consequences. Beyond the quantification of the physical impacts on mankind and the environment, the estimation of the external costs of the nuclear fuel cycle also raises some questions on the use of economic indicators such as the monetary value of statistical life, discount rates, or risk aversion.

Within the evaluation of the external costs of the nuclear fuel cycle, the estimation of the external cost associated with a nuclear accident has to be addressed. For this purpose,

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the usual approach consists of calculating the expected value of various accident scenarios (i.e. the sum of the accident scenario probabilities multiplied by their associated monetary consequences). The main criticism of this approach is that there is a discrepancy between the social acceptability of the risk and the average monetary value that in principle corresponds to the compensation of the consequences for each individual of the population affected by the accident. In fact, it appears that there is a need to integrate risk perception—risk aversion within the calculation of this external cost (Markandya, 1995).

Over the last decade, numerous valuations of the external cost of nuclear accident including risk aversion have been published. Some of them suggest that the expected value of the cost should be multiplied by a factor of up to 2000 to account for risk aversion (Gressmann, 1998). However, these approaches are not usually based on either sound empirical data or theory. The aim of this paper is to propose a methodology for the integration of risk aversion based on the expected utility approach. A numerical application based on the French data for the external cost of a nuclear accident is also presented.

General presentation of risk aversion and expected-utility approach

The simple calculation of the external cost associated with a nuclear accident is based on its expected value, that is the multiplication of the monetary consequences of the accident by the probabilities. This method usually leads to an underestimation of the 'social' cost because it does not take into account the risk perception of individuals. With the introduction of the expected utility criterion, it is assumed that when evaluating risk situations, individuals replace the monetary values of final wealth by the corresponding utility. This utility function characterizes attitude towards risk. Using the expected utility approach, it is possible to calculate a multiplying factor to be applied to the external cost of accident that takes individual-risk perception into account.

Selection of a utility function

From the theoretical point of view, various forms of utility functions can be constructed to reflect different attitudes towards risk. Many experimental studies have also been developed to estimate the risk aversion coefficient of individual decision-makers (e.g. Blake, 1996; Friend and Blume, 1975; Hansen and Singleton, 1982; Levy, 1994; Markandya, 1995; Mehra and Prescott, 1985; Szpiro, 1986; Weber, 1970). These studies usually show that absolute risk aversion decreases with wealth. As far as relative risk aversion is concerned,[1] they seem to support the idea of an almost constant coefficient of relative risk aversion.

As a consequence of this work on risk aversion, in this paper we use the power utility function defined by: $U(W)=[(1-\beta)/(\beta)]W^{\beta}$ with $\beta<1$. This function exhibits positive and decreasing absolute risk aversion ($A_a = (1-\beta)/(W)$) while the coefficient of relative risk aversion (A_r) is $(1-\beta)$. Notice that if the individual is risk neutral, the absolute and relative risk aversion coefficients are nil. The corresponding utility function is then taken to be: $U(W)=W$.

Calculation of the multiplying factor

To illustrate the evaluation of the multiplying factor, let us consider a risk situation characterised by N states of the world with probabilities $(p_1, p_2, \ldots, p_i, \ldots, p_N)$ and associated fractions of lost wealth $(X_1, X_2, \ldots, X_i, \ldots, X_N)$.

If the individual has a power utility function, his expected utility is given by:

$$E[U]=\frac{1-\beta}{\beta}\sum_{i=1}^{N} p_i(W(1-X_i))^{\beta} \qquad (1)$$

Denoting by M_A the maximum fraction of wealth that the risk averse individual would be willing to loose in exchange for avoiding

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[1] Absolute and relative risk aversion are properties of the utility function of wealth U(W). Absolute risk aversion is: $A_a=-(U''(W))/(U'(W))$ and relative risk aversion is: $A_r=-W(U''(W))/(U'(W))$, where $U'(W)$ and $U''(W)$ are respectively the first and second derivative of U(W). For details see for example, Eeckhoudt and Gollier (1995).

the lottery, we have:

$$E[\mathrm{U}]=\frac{1-\beta}{\beta}(\mathrm{W}(1-M_{\mathrm{A}}))^{\beta} \qquad (2)$$

which leads to:

$$M_{\mathrm{A}}=1-\left[\sum_{\mathrm{i}=1}^{\mathrm{N}}\mathrm{p_i}(1-X_{\mathrm{i}})^{\beta}\right]^{1/\beta} \qquad (3)$$

If instead, the individual were risk neutral, the maximum fraction of wealth he would be willing to loose (M_{N}) is given by:

$$M_{\mathrm{N}}=\sum_{\mathrm{i}=1}^{\mathrm{N}}\mathrm{p_i}X_{\mathrm{i}} \qquad (4)$$

The external cost of an accident is first calculated assuming risk neutrality. Then, in order to take account of risk aversion, the initial external cost must be multiplied by the following ratio:

$$\frac{M_{\mathrm{A}}}{M_{\mathrm{N}}}=\frac{1-\left[\sum_{\mathrm{i}=1}^{\mathrm{N}}\mathrm{p_i}(1-X_{\mathrm{i}})^{\beta}\right]^{1/\beta}}{\sum_{i=1}^{\mathrm{N}}\mathrm{p_i}X_{\mathrm{i}}} \qquad (5)$$

Numerical application for the external cost of a nuclear accident

The general methodology set out above can be illustrated by evaluating the external cost associated with an hypothetical nuclear accident, integrating risk aversion. For this calculation, the reference French scenario (called ST21) has been considered (Dreicer *et al.*, 1995).[2] After the determination of the different groups of population and states of the world, the monetary consequences of this nuclear accident are presented, and individual costs are calculated. Then, the question of risk aversion is addressed and a multiplying factor is estimated. Finally, the external cost of accident per kWh for the French nuclear fuel cycle is proposed.

Determination of the states of the world

The following assumptions are very closed to those selected in the ExternE project (Dreicer *et al.*, 1995). However, in the interests of simplification, some rounded numbers have been used.

Identification of the population

The total population potentially concerned with the effects of the accident is usually defined as the population around the nuclear power plant within a radius of 3000 km. However, because it is necessary to consider individual probabilities of damages, and in order to focus on the most significant probabilities for one coherent group of population, we assume here that the effects mainly concern the population within a radius of a few hundred of km, and that the total number of individuals is equal to the French population: 56 million inhabitants. Of course, if a nuclear accident did occur, it would not be exactly the population of a specific country which would be affected. However, the selection of one country, made for the sake of simplification, has the benefit of making the evaluation of the average individual financial wealth easier. Two areas are distinguished:

(1) Local, i.e. area around the nuclear power plant (< 100 km) where the inhabitants may be evacuated and relocated.[3] It is assumed that 2 million inhabitants are living in this area.[4] The distinction between relocated and non-relocated people will be made in the evaluation of the cost. The number of people concerned in each case depends on the selected scenario of accident. (2) Regional, the area further away from the power plant (> 100 km). Fifty-four million inhabitants are concerned.

Identification of the states of the world

In each area, it is possible to distinguish four 'states of the world' depending on the

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[2] This scenario corresponds, approximately, to a release of about one percent of the core for most of the relevant radionuclides.

[3] In the ExternE project, the farthest distance from the source for which it is realistically possible to implement acute countermeasures has been assumed to be 24 km for evacuation and 100 km for relocation.

[4] This corresponds approximately to the population living within a radius of 100 km around the French Tricastin Nuclear power plant (Dreicer *et al.*, 1995)

Table 1. Number of expected fatal and non-fatal effects

	Area	
	Local	Regional
Number of fatal cancers	410	2505
Number of severe hereditary effects	82	501
Number of non-fatal cancers	984	6012
Number of early diseases	2	0
Total Number of fatal effects	492	3006
Total Number of non-fatal effects	986	6012

potential radio-induced health consequences (fatal health effect, non-fatal health effect, no health effect and no accident) and their associated probabilities. The probability of each consequence depends on the selected scenario for the accident. Tables 1 to 3 show, for each area, the calculation of the probabilities corresponding to the scenario ST21. The probability of nuclear accident (leading to significant releases into the environment) is assumed to be in the order of 10^{-6} per reactor-year. The probabilities of fatal and non-fatal health effects are derived from the number of expected effects published in the ExternE study (Dreicer *et al.*, 1995) divided by the size of the population of each area.

Calculation of the monetary consequences

The calculation of the monetary consequences is mainly based on the economic module of COSYMA (Proult and Desaigues, 1993) with additional considerations on indirect costs (Schneider, 1998). On this basis, five main categories of cost can be distinguished (see Table 4): food bans, evacuation and relocation, indirect costs, fatal effect costs, non-fatal effect costs. For the calculation of the multiplying factor, it is necessary

Table 2. Estimation of individual probability of fatal, non-fatal and no effect

	Area	
	Local	Regional
Number of individuals (million of inhabitants)	2	54
Individual probability of fatal effects (π_1)	2·5 E-04	5·6 E-05
Individual probability of non-fatal effects (π_2)	4·9 E-04	1·1 E-04
Individual probability of no effect ($\pi_3 = 1 - \pi_1 - \pi_2$)	9·9926 E-01	9·9983 E-01

Table 3. Individual probability of damage for each state of the world

	Area	
	Local	Regional
Individual probability of accident (P)	1 E-06	1 E-06
Individual probability of accident and fatal effects ($P.\pi_1$)	2·5 E-10	5·6 E-11
Individual probability of accident and non-fatal effects ($P.\pi_2$)	4·9 E-10	1·1 E-10
Individual probability of accident and no effect ($P.\pi_3$)	9·993 E-07	9·998 E-07
Individual probability of no accident ($1 - P$)	9·99999 E-01	9·99999 E-01

Table 4. Total cost of the nuclear accident (ST21 Scenario)

Cost category	Local costs (MEuro)	Regional costs (MEuro)	Total cost (MEuro)
Food-bans	330	5832	6162
Evacuation and relocation	98	—	98
Fatal effects	1279	7816	9095
Non-fatal effects	247	1503	1750
Indirect costs	488	—	488
Total	2442	15 151	17 593

to express them as individual costs,[5] as presented below.

The food-ban costs are borne by individuals living in both local and regional areas:

- In the local area, the total food ban cost is evaluated at 330 MEuro and concerns two million inhabitants, which gives an individual cost of about 1·65E-04 MEuro.
- In the regional area, the total food ban cost is evaluated at 5832 MEuro and concerns 54 million inhabitants, which gives an individual cost of about 1·08E-04 MEuro.

The evacuation and relocation cost concerns only the local area and within this area, only the number of people who are assumed to be evacuated and relocated. It is assumed that the total cost of evacuation and relocation is 98 MEuro and concerns 9800 individuals, which gives an individual cost of about 1·00E-02 MEuro.

The indirect costs, borne only by local people, are assumed to be equal to 25% of the total local direct cost. The total local direct cost is equal to the sum of the food ban costs, the evacuation/relocation costs and the health effect costs. The individual cost of a fatal effect is assumed to be equal to 2·6 MEuro (monetary value of statistical life used in the ExternE study (Markandya, 1995)). The individual cost of a non fatal effect is assumed to be equal to 0·25 MEuro. For the local area, the total health effect cost is then 1526 MEuro (given the expected number of effects presented in Table 1 : 492 fatal effects and 986 non-fatal effects). Therefore, the total direct cost borne in the local area by two million inhabitants is 1954 MEuro, which gives a total indirect cost of 488 MEuro and an individual indirect cost of about 2·44E-04 MEuro.

Summary of individual costs

Table 5 summarises for each area, the total individual costs corresponding to each state of the world. The states of the world need to be separated into three groups of individuals, each group bearing a different set of costs:

(1) 1st group, local and relocated;
(2) 2nd group, local and not relocated;
(3) 3rd group, regional.

Determination of individual lotteries according to the loss of wealth

In order to calculate the multiplying factor to be applied to the cost of the accident, it is necessary to express the various costs as a percentage of individual loss of wealth. As, in the external costs study, the evaluation of the loss of individual wealth associated with the nuclear accident is based on the monetary value of life, as well as the loss of property, we assume that the wealth of an individual is made up of the following two components[6]: (1) The monetary value of statistical life (2·6 MEuro) (Markandya, 1995); (2) The average individual financial wealth (0·07 MEuro).[7]

On this basis, it is possible to express the individual costs in terms of percentage of individual wealth lost. The different lotteries faced by an individual are defined for each subgroup of population in Table 6.

Integration of risk aversion

Selection of a risk aversion coefficient

To integrate risk aversion within the calculation of the external cost of the nuclear accident, the value of the risk aversion coefficient to be adopted has first to be addressed. The empirical studies performed to estimate the relative risk aversion coefficient usually propose a coefficient between 0·5 and 2·5 (Friend and Blume, 1975; Hansen and Singleton, 1982; Szpiro, 1986; Weber, 1970). However, two very recent studies by Levy (1994) and Blake (1996) propose

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[5] In this paper, we did not take into account the possibility of insuring all or part of such costs. For discussions on the cost of insurance, see Dubin and Rothwell (1990), and Heyes and Liston-Heyes (1998).

[6] Notice that this assumption implies that in the case of a fatal effect, the loss of wealth corresponds to the monetary value of statistical life component and therefore not to 100% of the initial wealth (the average individual financial wealth still being available).

[7] The value of the average individual financial wealth is based on French data (Institut National de la Statistique et des Etudes Economiques, 1997): (1) private capital per household: 170 KEuro; (2) average number of persons per household: 2·5 persons.

Table 5. Total individual costs in each state of the world

Sub-group	States of the world	Individual costs of health effects (MEuro)	Individual food bans costs (MEuro)	Individual evac. +relocation costs (MEuro)	Individual indirect costs (MEuro)	Total individual costs (MEuro)
Local relocated	Local relocated + fatal effect	2·6	1·65 E-04	1·00 E-02	2·44 E-04	2·61
	Local relocated + non-fatal effect	0·25	1·65 E-04	1·00 E-02	2·44 E-04	2·60 E-01
	Local relocated + no health effect	0	1·65 E-04	1·00 E-02	2·44 E-04	1·04 E-02
Local not relocated	Local not relocated + fatal effect	2·6	1·65 E-04	—	2·44 E-04	2·60
	Local not relocated + non-fatal effect	0·25	1·65 E-04	—	2·44 E-04	2·50 E-01
	Local not relocated + no health effect	0	1·65 E-04	—	2·44 E-04	4·09 E-04
Regional	Regional + fatal effect	2·6	1·08 E-04	—	—	2·60
	Regional + non-fatal effect	0·25	1·08 E-04	—	—	2·50 E-01
	Regional + no health effect	0	1·08 E-04	—	—	1·08 E-04

Table 6. Lotteries faced by the three groups of individuals

Group	States of the world	% loss of wealth (X_i)	Probability (p_i)
First group, local and relocated individuals (N_1=9800 individuals)	Local relocated + fatal effect	97·75	2·5 E-10
	Local relocated + non-fatal effect	9·74	4·9 E-10
	Local relocated + no health effect	0·39	9·993 E-07
	No accident	0	9·99999 E-01
Second group, local and no relocated individuals (N_2=1 990 200 individuals)	Local not relocated + fatal effect	97·38	2·5 E-10
	Local not relocated + non-fatal effect	9·36	4·9 E-10
	Local not relocated + no health effect	0·02	9·993 E-07
	No accident	0	9·99999 E-01
Third group, regional individuals (N_3=54 millions individuals)	Regional + fatal effect	97·38	5·6 E-11
	Regional + non-fatal effect	9·36	1·1 E-10
	Regional + no health effect	0·004	9·998 E-07
	No accident	0	9·99999 E-01

much higher values. These authors derived the decision makers' utility functions from observed (portfolio) choices. These papers as well as a previous one by Mehra and Prescott (1985) produce a coefficient that can be as high as 47. Blake's (1996) study probably overestimates the true value of A_r because of its methodology. Indeed, the value of A_r he obtains is consistent with the high equity premium observed on stock markets. However, such a high premium may result from sources other than a high coefficient of relative risk aversion. In fact, when they make portfolio choices, decision-makers are aware that they bear many other risks than the ones attached to their portfolio (including general accident, health, etc...). Because of these other 'background' risks, they are probably very conservative towards portfolio risks so that the high equity premium results from two factors (and not from a single one): background risk and the degree of relative risk aversion.

Notice also that in the case of a nuclear accident, individuals are facing a lottery which is characterised by a high probability of no loss, and a very small probability of great loss (up to 98% of the initial wealth). It is then difficult to directly apply the values of a risk aversion coefficient which have been observed on the stock market, where the amount of potential loss is far less. In fact, applying a risk aversion coefficient greater than 2·5 to the 'nuclear accident lottery', to take into account the individual risk aversion, leads to absurd values of the certainty equivalent: the individuals would be willing to pay nearly the total cost of the consequences of the accident in order to avoid it, i.e. approximately all their wealth (the value of M_A increases exponentially with the increase in the relative risk aversion coefficient).

Therefore, according to the previous studies on risk aversion, we propose to choose a baseline value of 2 for the relative risk aversion coefficient. However, for the sake of comparison, we also produce the values of the multiplying factor when A_r is equal to 0·5, 1·2, 2·5 and 3.

Calculation of the multiplying factor

In order to obtain a total multiplying factor, it is first necessary to calculate the coefficient M_A (maximum percentage of wealth that a risk averse individual is willing to lose with certainty in order to avoid the accident) and M_N (maximum percentage of wealth that a risk neutral individual is willing to lose with certainty in order to avoid the accident) for each group of individuals, and then to calculate the ratio of the sum of these coefficients weighted by the size of the population of each group.

Let us call M_{A1}, M_{A2}, M_{A3} and M_{N1}, M_{N2}, M_{N3} the coefficients of the first, second and third groups of individuals, respectively under risk aversion (M_{Aj}) and under risk neutrality (M_{Nj}), and N_1, N_2, N_3 the population of each group. The total multiplying factor to be applied to the cost of the nuclear accident is obtained by the following formula:

$$M=\frac{N_1.M_{A1}+N_2.M_{A2}+N_3.M_{A3}}{N_1.M_{N1}+N_2.M_{N2}+N_3.M_{N3}} \qquad (6)$$

In this expression, we assume implicitly that the social cost of risk is the sum of the individual ones. However, such an 'additivity' assumption does not apply to some elements of the nuclear risk which are catastrophic in nature, but since the problem of non additivity raises some difficult theoretical questions it is not taken into account here.

Table 7 gives the value of M_A (maximum percentage of wealth that a risk averse individual is willing to lose with certainty in order to avoid the accident) and M_N (maximum percentage of wealth that a risk neutral individual is willing to lose with certainty in order to avoid the accident) for each group of individuals, both being calculated on the basis of the lotteries presented in Table 6.

The 'total' multiplying factor is then obtained by applying Equation (6) to the results of Table 7. It then appears that, with a risk aversion coefficient equal to 2, the expected external cost of an hypothetical nuclear accident such as the French scenario ST21 has to be multiplied by about 20 in order to integrate risk aversion.

Notice that the multiplying factor is, of course, quite sensitive to the value adopted for the risk aversion coefficient. The relationship between these two variables is presented in Table 8.

Table 7. Calculation of multiplying factor for each group of individuals

	First group local and relocated (j=1)	Second group local and no relocated (j=2)	Third group regional (j=3)
$M_{Aj}=1-\left[\sum_{i=1}^{4} p_i(1-X_i)^{-1}\right]^{-1}$	1·5 E-08	9·6 E-09	2·1 E-09
$M_{Nj}=\sum_{i=1}^{4} p_i X_i$	4·2 E-09	4·9 E-10	1·0 E-10

Table 8. Sensitivity analysis on the multiplying factor

Value of the relative risk aversion coefficient (Ar)	0·5	1·2	2	2·5	3
Multiplying factor (*M*)	2	2	20	83	385

Calculation of the external cost of the accident per KWh

The external cost of the hypothetical nuclear accident is calculated in three steps: (1) *Calculation of the expected value of the cost of accident.* This value, expressed in MEuro per reactor.year, is obtained by multiplying the total cost of the accident (see Table 4) by the probability of occurrence of the accident (in the case presented above, in which the accident has significant environmental releases, this probability is assumed to be in the range of 1E-06 per reactor-year). We obtain an expected value of the cost of the accident equal to 0·0176 MEuro reactor-year^{-1}. (2) *Calculation of the external cost of the nuclear accident, expressed in mEuro per kWh.* It is assumed here that the annual production of electricity of a reactor is equal to 7·6 TWh (Dreicer *et al.*, 1995). The external cost is obtained by dividing the expected value by this annual production. The external cost of the nuclear accident is then equal to 0·0023 mEuro kWh^{-1}. (3) *Calculation of the external cost of accident including risk aversion.* This value is obtained by multiplying the external cost by the multiplying factor calculated previously (M_A/M_N=20 in this case), which gives a value of 0·046 mEuro kWh^{-1}.

Conclusion

This paper shows that the calculation of the external cost of a nuclear accident that integrates risk aversion is feasible when an expected utility approach is applied. One of the advantages of this approach is the availability of experimental data concerning the relative risk aversion coefficient. Although a wide range of values have been published for this coefficient, mainly based on the analysis of financial risks, it seems reasonable to adopt a relative-risk aversion coefficient of around 2 for the specific case of nuclear accident. This leads to an estimated multiplying factor that is approximately equal to 20, to be applied to the expected external cost of a nuclear accident corresponding to a release of about one percent of the core. In this case, the external cost of the nuclear accident is estimated to be 0·046 mEuro kWh^{-1}. This represents about 50% of the total external cost of the nuclear fuel cycle without accident (estimated at 0·1 mEuro kWh^{-1} with a three percent annual discount rate).

Such a methodology could also be applied to the evaluation of the cost of other severe accidents, and some of its potential extensions might be considered in future research. For instance, besides the individual cost of risk, specific attention could also be paid to its social dimension. Indeed, in the case of a severe nuclear accident, two types of risk can be distinguished: (1) the first type corresponds to some effects of the accident (e.g. some health effects) which may affect each individual differently; (2) the second type concerns the occurrence of the nuclear accident itself which is imposed on the whole population.

In fact, the first type of risk is considered to be 'diversifiable' (in principle, individuals can cover the risk by an insurance contract) while the second is not. In this analysis, no distinction has been introduced, although preliminary studies in this field tend to show that the social cost of risk should be higher in the presence of 'non-diversifiable' risks than with equivalent diversifiable risks (Godfroid, 1996; Eeckhoudt and Godfroid, 1998). More work should be devoted to this topic in the future.

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