Ambiguity aversion and the expected-cost of rare energy disasters

The case of nuclear power accidents

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The paper

Observation Few and conflicting assessments of the nuclear risk

Questions How to make good decisions in this situation?

Is cost-benefit analysis appropriate when facing catastrophic risks?

Method Use of a growing literature on ambiguity-aversion

Results Generalization of cost-benefit analysis to situations of uncertainty

A method that accounts for public perceptions

Expected-cost of nuclear accidents 1.7€/MWh

Literature review

- Decision-making under ambiguity
  - Individual choice under ambiguity: Ghirardato (2004)
  - Combination of experts opinions: Gajdos (2008), Crès (2011)
  - Formalization of the precautionary principle: Henry (2002) (WP)
- Assesment of the nuclear risk:
  - Risk-aversion and nuclear accidents: Eeckhoudt (2000)
  - Statistical analysis of nuclear accidents: Hofert (2011), Wheatley (2016a,b)
  - Bayesian revision of nuclear experts opinions: Rangel (2014)

Not a new question...

- "*In the actual exercise of reason we do not wait on certainty, or deem it irrational to depend on a doubtful argument.*" J. M. Keynes (A Treatise on Probability, 1920)

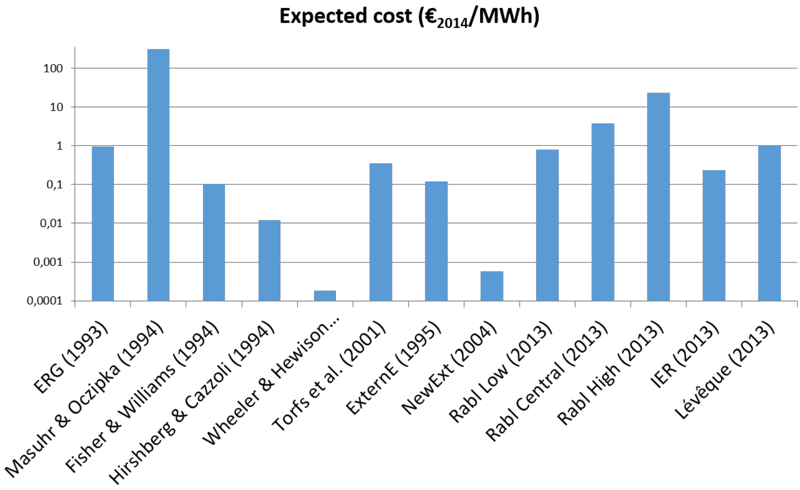
Outline of the presentation

1. Motivation and challenges
2. Uncertainty and economic theory of decision
3. An application to nuclear power accidents
4. Limits and policy implications

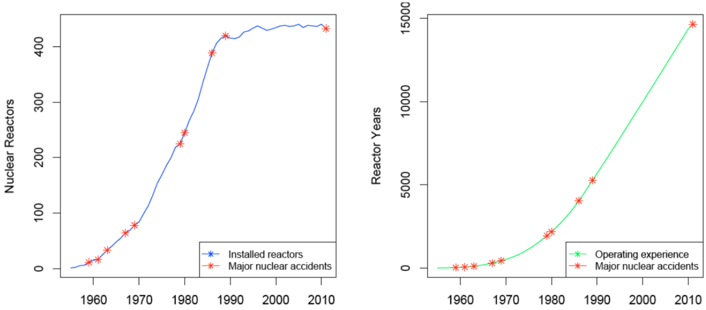
Motivations

- A need to estimate the cost of nuclear accidents
  - To better inform policy/investment decisions
  - examples: nuclear share in the energy mix, location of nuclear stations, phase-out schedules
- An estimation facing important methodological challenges
  - Rare events whose frequencies are not probabilities
  - Absence of consensus on the expected-cost of accidents

No consensus on expected-costs



Few observations of nuclear power accidents



INES	3	4	5	6	7
Observations	20	13	5	1	2

Figure: Historic occurrences of severe nuclear events (Cochran, 2011)

No consensus in the measurement of probabilities

Figure: Existing studies assessing nuclear accident probabilities

Source	Year	Core melts	Large releases	Method
ExternE	1995	5.10^{-5}	1.10^{-5}	PSA
NEA	2003	10^{-5}	10^{-6}	ExternE (PSA)
Hofert, Wuthricht	2011	1.10^{-5}	NS	Poisson law
IRSN	2012	NS	10^{-5}-10^{-6}	IAEA standards
Rabl	2013	NS	10^{-4}	Observed frequencies
IER	2013	NS	10^{-7}	NS
D'Haeseleer	2013	$1,7.10^{-4}$	$1,7.10^{-5}$	Bayesian update
Rangel, Lévêque	2014	$4,4.10^{-5}$	NS	PEWMA model

Interpretation for a 400-reactor fleet

- $p_{PastEvents} = 10^{-4}$: one major accident every 25 years
- $p_{PSA} = 10^{-6}$: one major accident every 2500 years

Accident frequencies are not objective probabilities

The **number of repetitions** does not allow identification :

- 14,500 observed Reactor.Year
- Few observed events
  - Cochran (2011): 12 CMD since 1955
  - Extension to INES > 2: 41 events since 1991

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The **i.i.d. hypothesis** is not respected :

- **Not identically distributed** - Diversity of accident types, of reactor technology or location, of safety regulators...
- **Not independent** - Accidents affect safety standards

What about PSAs?

Estimating probabilities with PSA

- Based on event-trees and simulations
- Pinpoint local safety weaknesses
- Better allocate safety efforts

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What information do they carry?

- 40 years of nuclear engineering knowledge
- Assuming safety standards are well enforced
- Assuming no unknown unknowns

What about public perceptions?

Public perceptions should be accounted for

- Possible additional costs
- Super-Phenix, Takahama

Experimental psychology works

- Perceptions can be distorted
- Rare events are perceived as more likely than they are (Lichtenstein, 1978; Slovic, 1982).
- Dreadful events are perceived as more likely than they are (Kahneman, 2011)

Nuclear accidents are both rare and dreadful

Stakes for the decision maker

The sources are conflictual

PSA for a large accident in an EPR: 10^{-7}

Observed frequency of large accidents: 10^{-4}

Perceptions: $> 10^{-4}$?

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Perceptions: $> 10^{-4}$?

Which information should be relied on?

All sources are biased

Using a biased probability could entail:

- wrong level of investments in safety
- wrong timing of phase-outs
- suboptimal technology mixes

How can policy-makers make good decisions in these situations?

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Cost-benefit analysis (CBA)

- Objectives
  - Basis for comparison of competing projects
  - Implicitly, best decision maximizes *benefits* − *costs*
- Underlying hypotheses:
  - Costs and benefits can be given monetary values
  - Risks can be given a probabilistic representation
  - All agents agree on this representation
- Shortcomings
  - What monetary values for non-monetary consequences?
  - How to include attitude towards risks and uncertainties?

Risks and uncertainty (Knight, 1920)

Risk Various outcomes associated with probabilities
Repetition confirms the probability representation

Uncertainty Various outcomes without attached probabilities

Examples

Risk: roll of dice, roulette wheel...
Uncertainty: Horse races, elections, long-term weather forecasts...

Decisions and economics

Bayesian Decision-Making (Gilboa, 2004)

1. All risk can be represented in probabilistic terms
2. Preferences and beliefs are updated using Bayes' law
3. "Good decisions" consist in the maximization of an expected utility w.r.t probabilistic beliefs

Main authors: de Finetti, Von Neumann, Morgenstern, Savage.

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Non-Bayesian Decision-making

Challenging 3: Allais, Kahneman, Tversky
Challenging 2: Kahneman, Tversky
Challenging 1: Modern decision theory

Ambiguity - Ellsberg's paradoxes

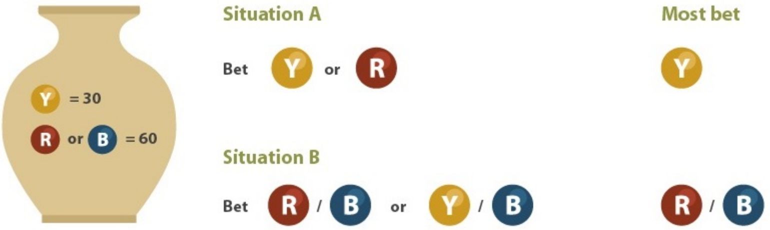


Figure: The one-urn Ellsberg paradox

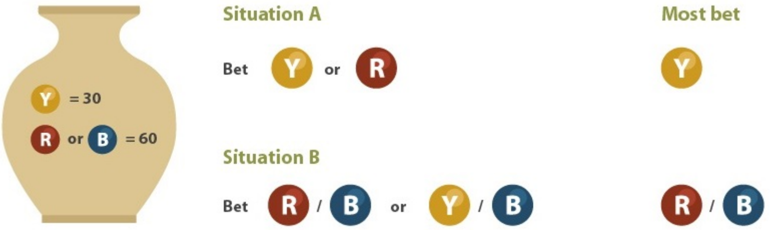


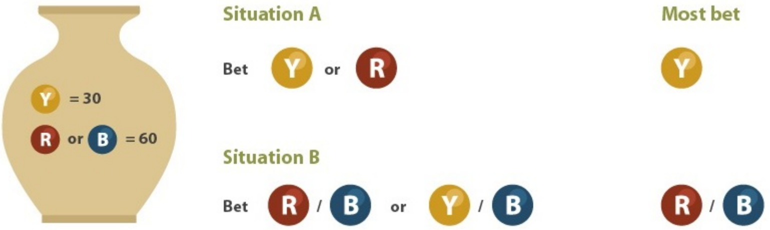
Figure: The one-urn Ellsberg paradox

Situation A $\mathbb{P}(Y) > \mathbb{P}(R)$

Situation B $\mathbb{P}(Y \cup B) < \mathbb{P}(R \cup B) \Rightarrow \mathbb{P}(Y) < \mathbb{P}(R)$

Ambiguity - Ellsberg's paradoxes

Figure: The one-urn Ellsberg paradox



- People prefer bets described by known probabilities
- Ambiguity-aversion is not accounted for in classical cost-benefit analysis

1 Motivation and challenges

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4 Limits and policy implications

The decision rule (1/2)

- We apply a decision criterion (GMM, 2004)
- Decision Maker is assumed to behave according to six axioms:

Ghirardato's "rationality" (2004)

- **GMM1:** Transitive Weak-order (usual)

$$\mathbf{a} \succeq \mathbf{b} \textit{ and } \mathbf{b} \succeq \mathbf{c} \Rightarrow \mathbf{a} \succeq \mathbf{c}$$

- **GMM2:** Certainty Independence (new)
- **GMM3:** Continuity (technical, usual)
- **GMM4:** Monotonicity (usual)
- **GMM5:** Non-degeneracy (trivial)
- **GMM6:** Certainty-equivalence (new, technical)

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- **GMM1:** Transitive Weak-order (usual)
- **GMM2:** Certainty Independence (new) "*risk hedging*":

$$\mathbf{a} \preceq \mathbf{b} \Leftrightarrow \lambda\mathbf{a} + (1-\lambda)\mathbf{c} \preceq \lambda\mathbf{b} + (1-\lambda)\mathbf{c}, \;\; \mathbf{c} \text{ constant}$$

- **GMM3:** Continuity (technical, usual)
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- **GMM3:** Continuity (technical, usual) "*no extreme*"

$$\mathbf{a} \prec \mathbf{b} \prec \mathbf{c} \Rightarrow \lambda_1 \mathbf{a} + (1-\lambda_1)\mathbf{c} \prec \mathbf{b} \prec \lambda_2 \mathbf{a} + (1-\lambda_2)\mathbf{c}$$

- **GMM4:** Monotonicity (usual)
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- **GMM4:** Monotonicity (usual) "*state dominance*"

$$\forall s \in \mathcal{S}, b(s) \preceq a(s) \Rightarrow \mathbf{b} \preceq \mathbf{a}$$

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$$\exists \mathbf{a}, \mathbf{b}, \ \mathbf{a} \preceq \mathbf{b}$$

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$$\forall \mathbf{a}, \mathbf{b} \in \mathbf{A}, C^*(\mathbf{a}) = C^*(\mathbf{b}) \Rightarrow \mathbf{a} \sim \mathbf{b}.$$

The decision rule 2/2

A simple, equivalent interpretation

- Uncertainty represented by a set of probabilities
- Decisions based on expected-costs, calculated w.r.t. **worst case** and **best case** probabilities
- Attitude towards ambiguity captured by **parameter** ($\alpha \in [0; 1]$)
  - $\alpha = 1$: decisions are based on the worst case
  - $\alpha = 0$: decisions are based on the best case

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In other words, the expected-cost is a weighted sum

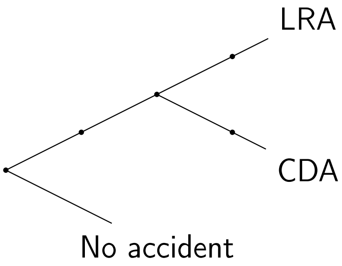
$$\mathbb{E}_\alpha C = \alpha \mathbb{E}_{\textit{worst case}}[C] + (1-\alpha)\,\mathbb{E}_{\textit{best case}}[C]$$

Underlying structure

Two categories of accidents

- Core Damage Accident without releases (CDA)
- Large-Release Accident (LRA)

Figure: A simplified event-tree structure for nuclear accidents



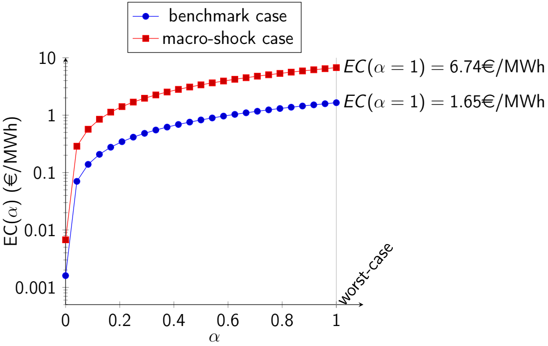
Hypotheses concerning nuclear accidents

Table: Hypotheses regarding damage and probabilities

	Probability (per r.y)		Damage (10^9€)	
	best-case	worst-case	benchmark	macro
Core-damage	10^{-6}	10^{-3}	$2,6$	52
Large-release	10^{-7}	10^{-4}	170	359
Source	AREVA (HSE PSA)	Past events	Sovacool (08) Jap. Gvt.	IRSN (13) Rabl (13)

The expected-cost of nuclear accidents

Figure: Expected-cost in €/MWh as a function of α



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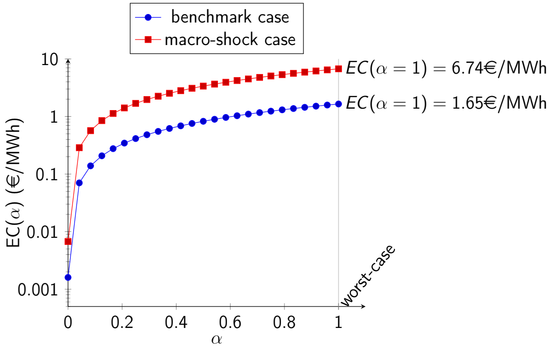

- worst case scenario - $1.7€/MWh$
- worst scenario with macro consequences $7€/MWh$

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Policy implications

Policy Assessments of the costs of technologies should account for public perceptions as well as experts analyses

Nuclear Our result is *small* when compared to the LCOE of nuclear power new builds ($\sim$ 100€/MWh)

Method Other uses to assess the cost of other rare disasters (oil spills, dam failures, nuclear safety standards or accident mitigation plans...)

Limits

Damage: are also prone to uncertainties

Completeness: All states of the world not known *ex ante*

Flexibility: Decisions are good *ex ante*

What happens when new information is obtained?

Is *ex post* flexibility valuable? (Kreps (1979))

Social choice: Implicit assumption: decision-maker is a rational individual (firm CEO, banker, median voter...)

No aggregation of preferences (equity concerns)

Thank you for your attention !

More information and references :

- www.cerna.mines-paristech.fr/leveque/
- www.cerna.mines-paristech.fr/bizet/
- www.cerna.mines-paristech.fr/nuclearpower/

Appendix 1: Decision rules

General form of decision criteria in economic theory

Rationality = conditions on preferences (or axioms) $\Leftrightarrow$ Decisions maximize an index I:

$$d_1 \preceq d_2 \Leftrightarrow I(d_1) \leq I(d_2)$$

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Decisions under risk

Expected utility: $I(d) = \sum_S p(s)u(d(s))$

Decision and ambiguity

Maxmin Expected Utility: $I(d) = \min_{\pi \in \Pi} E_\pi[U(d)]$

Many other criteria

Appendix 2: References I

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