Ambiguity aversion and the expected cost of rare energy disasters

The case of nuclear power accidents

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- "*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)
- "*Probability does not exist* " B. De Finetti, (Theory of Probability, 1974)

Background

- A research program dedicated to nuclear power economics hosted since 2010 at Mines ParisTech and financed by EDF
- Two research axes
  - The analysis of the costs of nuclear power generation
  - The governance and regulation of nuclear safety
- Outcomes:
  - One book: *The Economics and Uncertainties of Nuclear Power* (Cambridge U. Press)
  - 5 peer-reviewed papers, 3 on-going working papers, 2 PhD theses
- Website: http://www.cerna.mines-paristech.fr/nuclearpower/

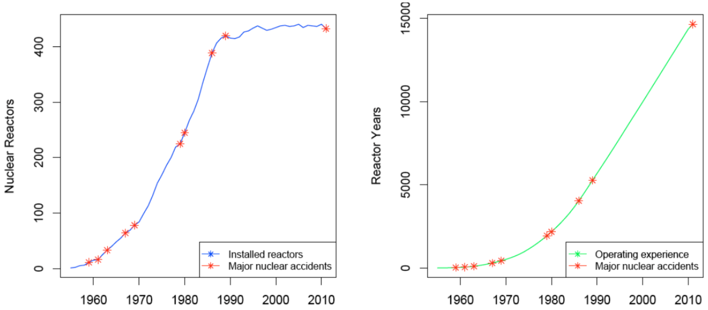
Outline of the presentation

1. Motivations and challenges
2. Uncertainty and economic theory of decision
3. The case of 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

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

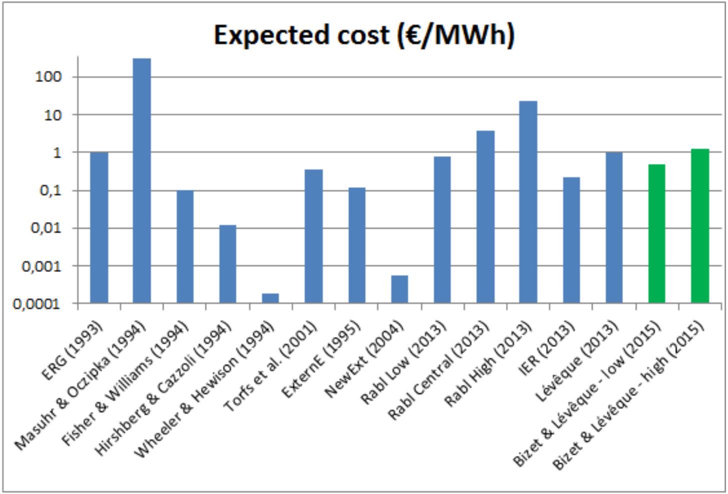
Source	Year	Core melts	Large releases	Method
ExternE	1995	5.10^{-5}	1.10^{-5}	PSA
NEA	2003	10^{-5}	10^{-6}	ExternE (PSA)
Hofert, Wuthricht	2011	1.10^{-5}	NS	Poisson law
IRSN	2012	NS	10^{-5}-10^{-6}	IAEA standards
Rabl	2013	NS	10^{-4}	Observed frequencies
IER	2013	NS	10^{-7}	NS
D'Haeseleer	2013	$1,7.10^{-4}$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

No consensus on expected costs

Figure: Existing assessments of the expected cost of nuclear accidents



The paper

Observation	Scarce but ambiguous assessments of the nuclear risk
Questions	How to make good decisions in this situation? How to account for attitudes towards risks and uncertainties?
Method	Use of a growing literature on ambiguity-aversion
Results	Generalization of cost-benefit analysis to situations of uncertainties 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)
- Assesement 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: Lévêque (2014)

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

Decision rules

General form of decision criteria in economic theory

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

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

Decision under risk

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

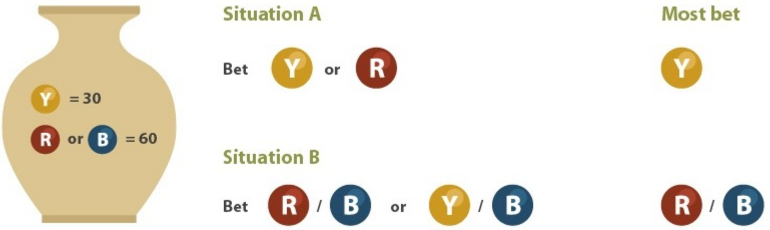
Decision under uncertainty

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

Many other criteria

Ambiguity - Ellsberg's paradoxes

Figure: The one-urn Ellsberg paradox

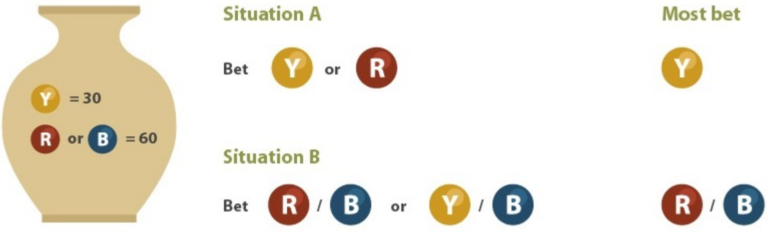


Situation A $\mathbb{P}(Y) > \mathbb{P}(R)$

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

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 probabilistic safety assessments?

Estimating probabilities with PSA

- Several PSA codes exist: COSYMA, E3X...
- Calculations based on event-trees
- Designed to pinpoint local safety weaknesses and remedies, not to calculate a single number and its confidence interval

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: they should be accounted for

additional costs due to the resentment of policies or technologies

Experimental psychology: distorted perceptions

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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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?

Nuclear accidents are uncertain events

Ambiguous information on probabilities

- Observed frequencies are not probabilities
- People's perceptions are biased
- Experts' calculations are imperfect

How can we overcome this uncertainty?

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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- **GMM2:** Certainty Independence (new) "*risk hedging*":

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

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

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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
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In other words, the expected cost is a weighted sum

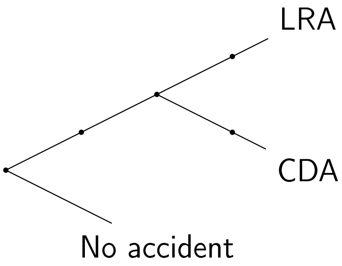
$$\mathbb{E}_\alpha C = \alpha \mathbb{E}_{\textit{worst case}}[C] + (1-\alpha)\,\mathbb{E}_{\textit{best case}}[C]$$

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

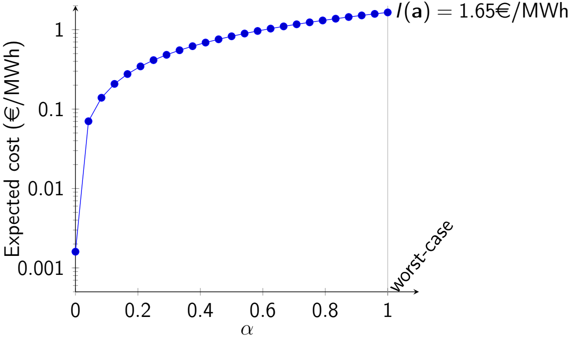
Table: Hypotheses regarding damage and probabilities

	damage (10^9€)	best-case probability	worst-case probability
core-damage	$2,6$	10^{-6}	10^{-3}
large-release	180	10^{-7}	10^{-4}

Sources Damage: Sovacool (2008) and IRSN (2013)
Probabilities: AREVA and past events

The expected cost of nuclear accidents

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



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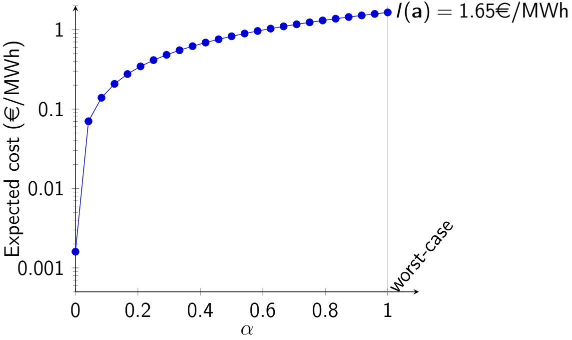

- worst case scenario - 1.7€/MWh
- worst scenario with macro consequences 7€/MWh

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 (~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

Incompleteness all states of the world not known *ex ante*

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/

References I

Crès, H., Gilboa, I., and Vieille, N. (2011). Aggregation of multiple prior opinions. *Journal of Economic Theory*, (146):2563–2582.

Eeckhoudt, L., Schieber, C., and Schneider, T. (2000). Risk aversion and the external cost of a nuclear accident. *Journal of Environmental Management*, pages 109–117.

Gajdos, T., Tallon, J.-M., and Vergneaud, J.-C. (2008). Representation and aggregation of preferences under uncertainty. *Journal of Economic Theory*, (141):68–99.

Ghirardato, P., Maccheroni, F., and Marinacci, M. (2004). Differentiating ambiguity and ambiguity attitude. *Journal of Economic Theory*, 118:133–173.

Henry, C. and Henry, M. (2002). Formalization and applications of the precautionary principles. Columbia Discussion Papers Series.

References II

Hofert, M. and Wüthrich, M. V. (2011). Statistical review of nuclear power accidents. *Asia-Pacific Journal of Risk and Insurance*, 7:1–13.

Kreps, D. M. (1979). Preference for flexibility. *Econometrica*, 47(3):565–577.

Rangel, L. E. and Lévêque, F. (2014). How fukushima dai-ichi core meltdown changed the probability of nuclear accidents ? *Safety Science*, 64:90–98.

Wheatley, S., Sovacool, B. K., and Sornette, D. (2016a). Of disasters and dragon kings: a statistical analysis of nuclear power incidents and accidents. *Risk analysis*.

Wheatley, S., Sovacool, B. K., and Sornette, D. (2016b). Reassessing the safety of nuclear power. *Energy Research & Social Science*, 15:96–100.