The economic assessment of the risks of nuclear power accidents

Bayesian and non-Bayesian approaches

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Introduction

- Why is it important to estimate the costs of nuclear accidents?
  - to compensate victims
  - to make better ex-ante decisions (location, phase-out, technology choices)
- Main differences between ex ante/ex post assessments
  - Economics/cost accounting and auditing
  - uncertainties on future/past
  - damage or probability $\times$ damage?
- This presentation:
  - How should we revise the probability of nuclear core meltdowns after the Fukushima Dai-Ichi accident ? (Rangel and Lévêque, 2014)
  - A method for the calculation of the expected cost of nuclear accidents (Bizet and Lévêque, 2016)

Outline

1. The effect of Fukushima Dai-ichi on the probabilities of nuclear power accidents (Rangel and Lévêque, 2014)
   - Motivation and literature review
   - Combining observations and PSAs
   - The effect of Fukushima on the probabilities of accidents
2. Ambiguity and the expected costs of nuclear power accidents (Bizet and Lévêque, 2016)
   - Motivations and existing assessments
   - Overcoming ambiguity
   - New method and policy implications

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Two streams of literature

- Existing statistical studies
  - Poisson models and fat-tailed distributions based on scarce accident data
  - Hofert and Wüthrich (2011), D'Haeseleer (2013)
- Industry Probabilistic Safety Assessments (PSA)
  - In the US: WASH 1400 (1975), or in Europe: ExternE (1995)
  - More recent studies Kadak and Matsuo (2007), and EPRI (2008)

No consensus

There is no agreement on the value of the probability:

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

The research question

- A methodological question:
  - Can we reconcile the observations of nuclear accidents with the theoretical practice of PSAs?

- An applied question:
  - How should we revise the probabilities of nuclear core meltdown after the Fukushima Dai-Ichi accident?

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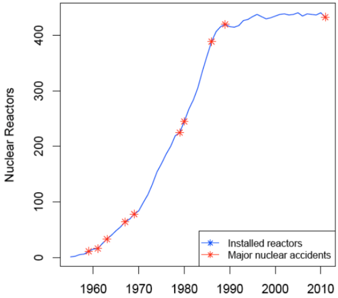
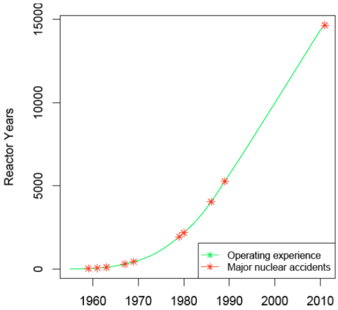
The observations of nuclear power accidents





Year	Location	Unit	Reactor type
1959	California, USA	Sodium reactor experiment	Sodium-cooled power reactor
1961	Idaho, USA	Stationary Low Reactor	Experimental gas-cooled, water moderated
1966	Michigan, USA	Enrico Fermi Unit 1	Liquid metal fast breeder reactor
1967	Dumfreshire, Scotland	Chapelcross Unit 2	Gas-cooled, graphite moderated
1969	Loir-et-Chaire, France	Saint-Laureant A-1	Gas-cooled, graphite moderated
1979	Pennsylvania, USA	Three Mile Island	Pressurized Water Reactor (PWR)
1980	Loir-et-Chaire, France	Saint-Laureant A-1	Gas-cooled, graphite moderated
1986	Pripyat, Ukraine	Chernobyl Unit 4	RBKM-1000
1989	Lubmin, Germany	Greifswald Unit 5	Pressurized Water Reactor (PWR)
2011	Fukushima, Japan	Fukushima Dai-ichi Unit 1,2,3	Boiling Water Reactor (BWR)

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

- 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

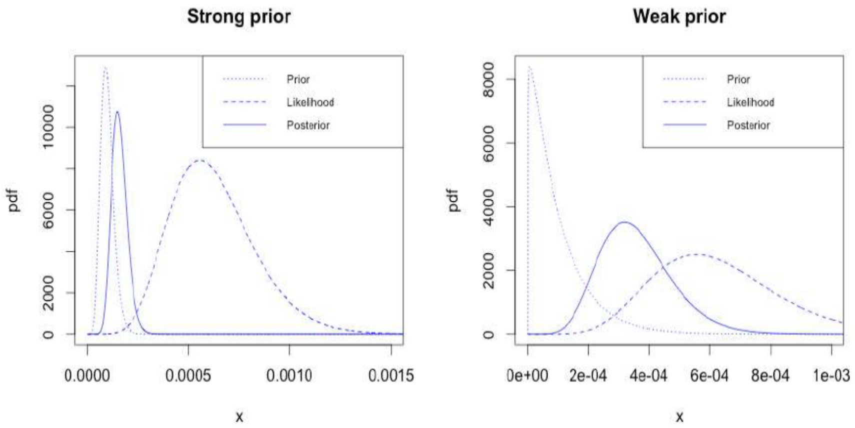
What information do they carry?

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

The Bayesian revision framework

- What are the odds of drawing a red ball from an urn, when the n previous draws yielded k red balls ?
- According to Laplace (french mathematician, 1825) : $\frac{k+1}{n+2}$
  - as if two virtual draws yielded one red and one not-red.
- More generally : $\frac{k+st}{n+s}$
  - t: prior regarding the probability of obtaining a red ball, and
  - s: strength of the prior
- For a given problem, s and t can be based on scientific knowledge, or on beliefs

Priors and posteriors



What about nuclear accidents?

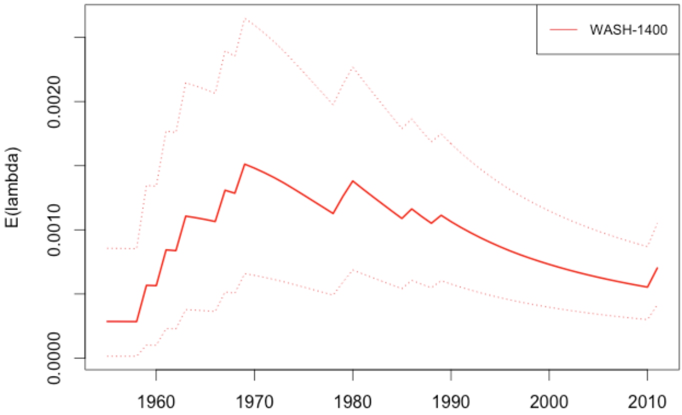
Two contradicting forces

- Increasing safety levels and long periods of time without accidents suggest a decreasing trend in the probabilities of core meltdowns
- Observation of nuclear accidents trigger an upward revision of probabilities to take into account the new pieces of information.

Bayes' rule allows the combination of PSA and observations

1. PSAs are the prior probability of nuclear accidents
2. Each year, the prior is updated, using Bayes rules:
   - if no accident: posterior probability $\leq$ prior probability
   - if accident: posterior probability $\geq$ prior probability

Combining observations and PSAs



Bayesian Poisson Gamma Model, Rangel and Lévêque (Safety Science, 2014).

The post-Fukushima probabilistic update

- Four Poisson models
  - Poisson models usually assume independence
  - PEWMA Model allows to introduce a degree of dependence

- Main results: changes in the expected frequency of nuclear accidents

Summary of results.

Model	$\hat{\lambda}_{2010}$	$\hat{\lambda}_{2011}$	Δ
MLE Poisson	6.175e−04	6.66e−04	0.0790
Bayesian Poisson–Gamma	4.069e−04	4.39e−04	0.0809
Poisson with time trend	9.691e−06	3.20e−05	2.303
PEWMA model	4.420e−05	1.95e−03	43.216

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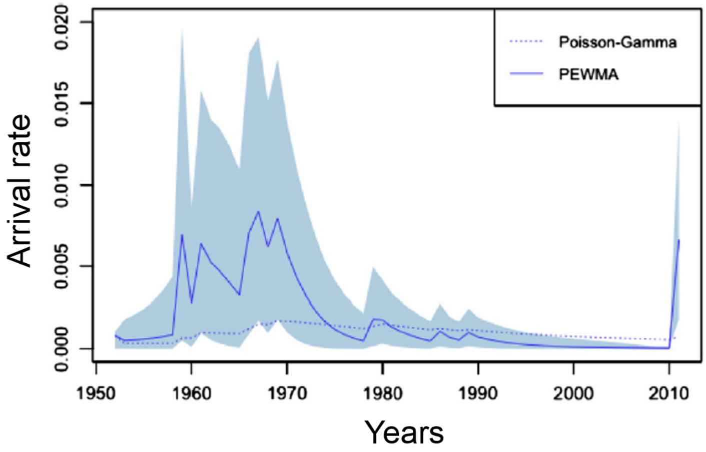

Poisson Exponentially Weighted with Moving Average model, Rangel and Lévêque (Safety Science, 2014).

Interpretations

- The risk of nuclear accident has to be significantly revised upward after the Fukushima disaster
- This revision embodies the learnings from the accidents:
  - PSAs assume perfect compliance, which is untrue
  - Competent safety regulators have to be independent, transparent and powerful
- More generally, this revision embodies the idea that upgrading nuclear safety regulators around the world could be a significant source of safety improvements

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The cost of nuclear accidents

The initial question

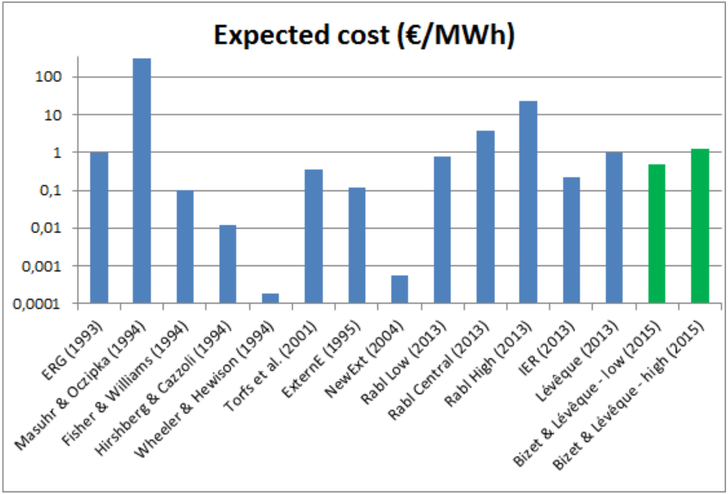
- How should rare but catastrophic accidents be taken into account in nuclear policy decisions?
- What is the expected cost of a nuclear accident in the case of a new-build nuclear reactor?

The main steps of the study

- Review of the existing sources of information regarding the risks of nuclear accidents
- Analysis of the ambiguity that characterizes these accidents
- Proposition of a new methodology for the assessment of the expected cost of rare disasters

Assessments of the expected costs

Figure: Existing assessments of the expected cost of nuclear accidents



Focus on probabilities

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- PSAs assume perfect compliance
- Past frequencies are not probabilities

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?

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Risks and uncertainty (Knight, 1920)

Risk: Various outcomes measured by a probability.
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Uncertainty: Various outcomes without attached probabilities.

Examples

Risk: roll of dice, roulette wheel...

Uncertainty: Horse races, elections, long-term weather forecasts...

Nuclear accidents are uncertain events

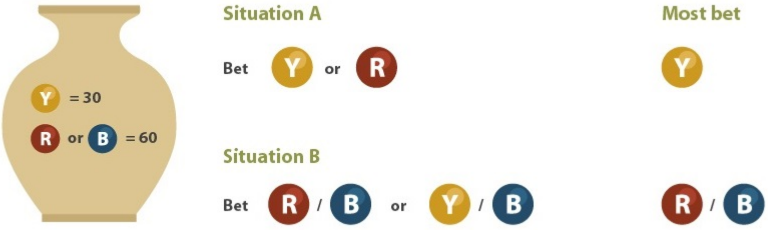
Multiple, conflicting information on probabilities

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

How can we overcome this uncertainty?

Ambiguity - Ellsberg's paradoxes

Figure: The one-urn Ellsberg paradox



- People prefer to bet with known probabilities
- Ambiguity-aversion is not accounted for in classical cost-benefit analysis

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Adaptation to the calculation of the expected cost

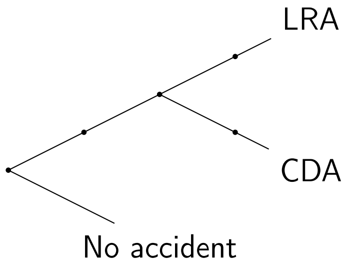
$$\mathbb{E}_\alpha C = \alpha \mathbb{E}_{\textit{worst case}}[C] + (1-\alpha)\, \mathbb{E}_{\textit{best case}}[C]$$

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 damage

Table: Nuclear damage, for an EPR in the UK, in **billions of euros**

	Estimated damage
D_{CDA}	$2,6$
D_{LRA}	180

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Sources

Cost of TMI by Sovacool (2008)

Cost of a LRA estimated by IRSN (2013)

Hypotheses concerning the probabilities

Table: The probabilities, expressed per *reactor.years*

	Best prior	Worst prior
$p(CDA)$	10^{-6}	10^{-3}
$p(LRA)$	10^{-7}	10^{-4}

Two *priors* to describe uncertainties

The best-case prior

- AREVA's achieved target for the EPR safety

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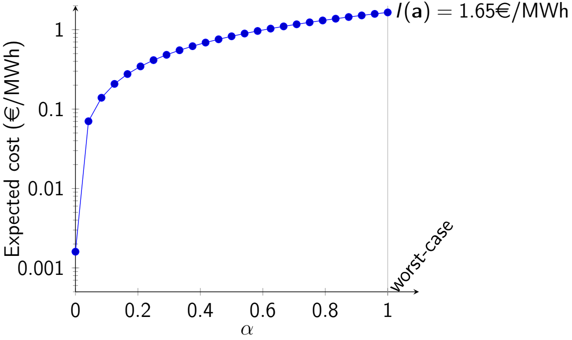
The worst-case prior

- Probabilities based on the observed frequency of past accidents (1 LRA every 25 years)

The expected cost of nuclear accidents

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



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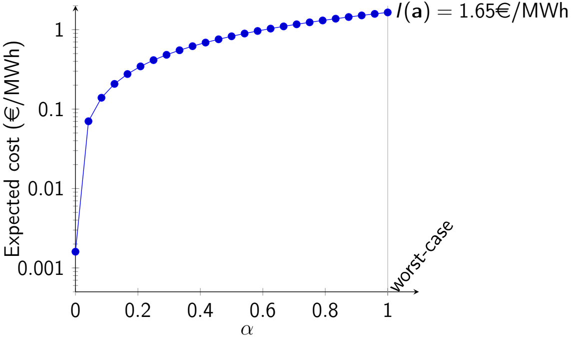

- worst case scenario - 1.7€$/MWh$
- worst scenario with macro consequences 7€$/MWh$

Policy implications

Nuclear policies : The cost found in this study is small when compared to the LCOE of nuclear power new builds

The expected cost of nuclear accidents ought to reflect public perceptions as well as technical investigations

The method can be used to assess the expected cost of other rare disasters subject to ambiguous probabilities, or other policies

Rare disasters: oil spills, dam failures...

Policy analysis: nuclear safety regulation analysis or accident mitigation plans

Conclusion

- Two methodological contributions for the combination of technical knowledge, experience and perceptions
  - A Bayesian revision framework to account for new events in the assessment of nuclear accident probabilities
  - A non-Bayesian method to combine technical knowledge and uncertainty-averse individual preferences
- Nuclear power policy implications
  - An important and untechnical upgrade of nuclear safety consists in the improvement of the quality of safety regulators around the world
  - The expected costs of nuclear accidents are small compared to the construction costs of new builds

Thank you for your attention !

More information and references :

- www.cerna.mines-paristech.fr/fr/leveque/
- www.cerna.mines-paristech.fr/fr/bizet/
- www.cerna.mines-paristech.fr/fr/recherche/economics-nuclear

The economic estimation of nuclear damage

Figure: Assessments of the cost of a nuclear accident, in billion euros