Formalizing Quantitative Risk Analysis

Probabilistic foundations & Monte Carlo simulation

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Background and Motivation

- Quantitative Risk Analysis, QRA, estimates how often hazardous events happen and severity.
- Supports safer design, better emergency planning, and clearer communication with the public.
- Seveso III directive requires systematic risk assessment for sites that handle dangerous substances.
- Sweden implements Seveso through national rules and oversight by MSB, and the permits for these sites require a documented QRA.

Case example, Visakhapatnam gas leak 2020

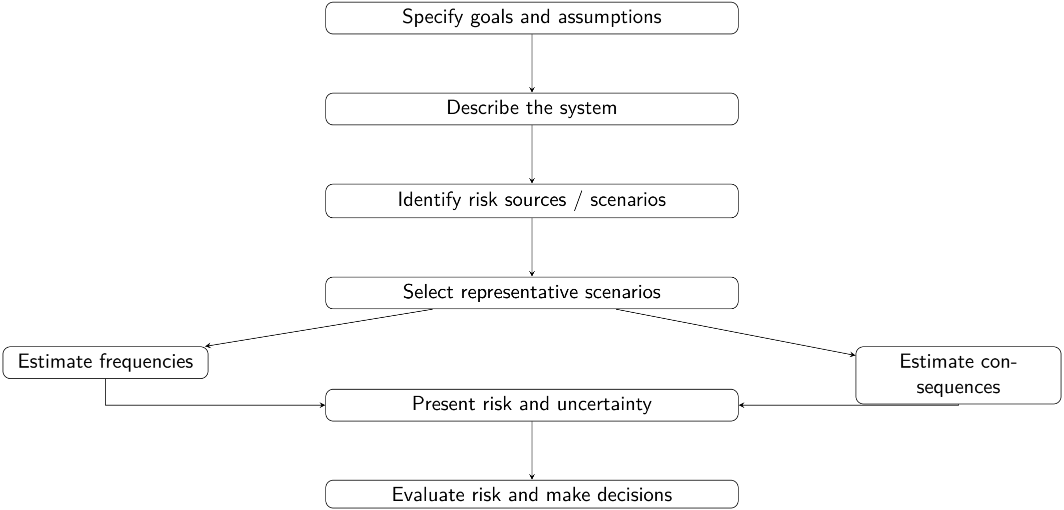
- A styrene vapour release occurred near homes.
- The early-morning plume surprised residents.
- There were several deaths and many injuries.
- This shows the need for robust risk analysis.

[1] BBC News, Visakhapatnam styrene leak 2020

Research Questions and Objectives

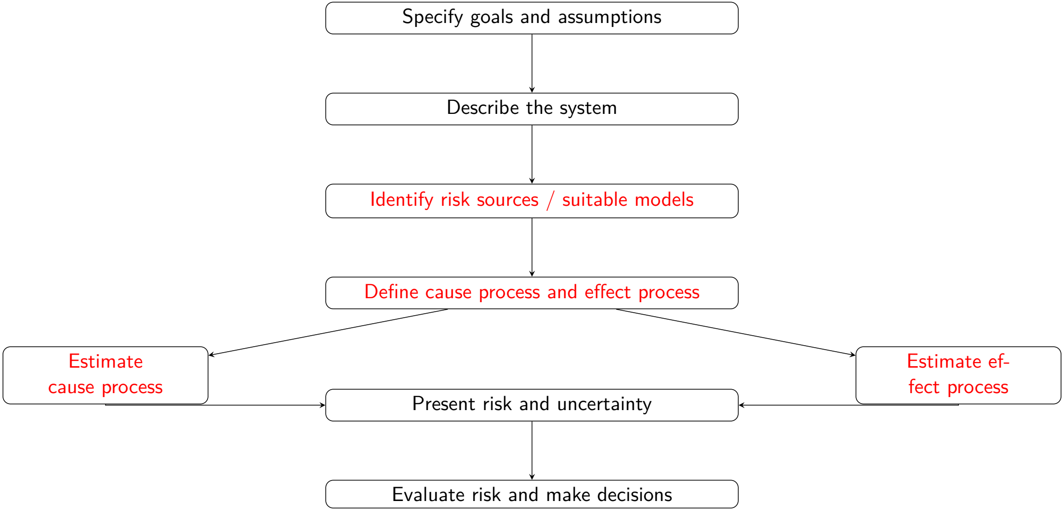
- **Formalizing risk metrics:** Recast risk measures using probability theory.
- **Scenario vs. Monte Carlo:** Compare the scenario and Monte Carlo approaches.
- **Modularity and efficiency:** Design a modular framework for reusable analyses.

Risk Analysis Process

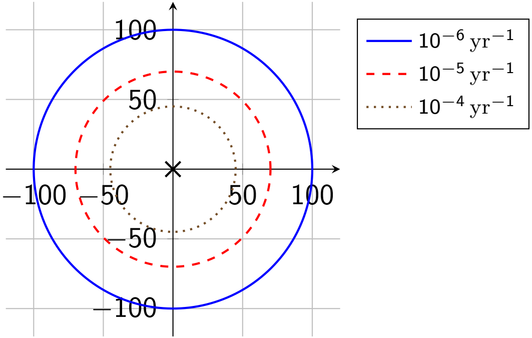


[2]F2a-b, Att undersöka risk och säkerhet i sociotekniska system, Henrik Hassel Lund University

Updated Risk Analysis Process

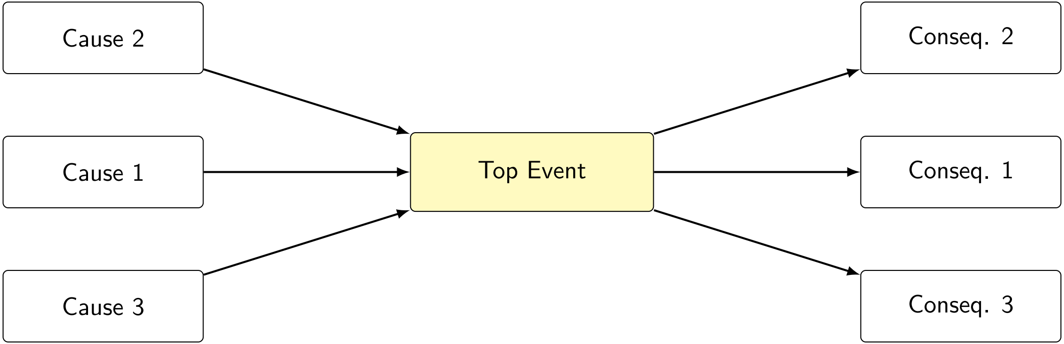


Individual Risk



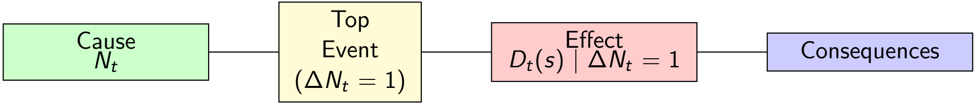
- **Definition.** Individual risk is the annual likelihood that a person at a fixed location will die.
- **Comparison.** Lightning causes about one death per million people per year.
- **Example.**A leak frequency of 10^{-4} per year with a 10% fatality at rate at 70 m yields a risk of 10^{-5} per year.

Bow Tie Model



- Causes are on the left,
- The top event is in the center,
- Consequences are on the right.

Updated Bow Tie Model



- The cause is a counting process N_t over time.
- A top event happens when $\Delta N_t = 1$.
- The consequences are represented by the probability of death $D_t(s)$.
- We simulate time and weather to evaluate $D_t(s)$.

Formalizing risk metrics: Individual risk

Scenario method

$$IR(x,y) \;=\; \sum_{i=1}^{n} f_i \, p_{f,i}(x,y)$$

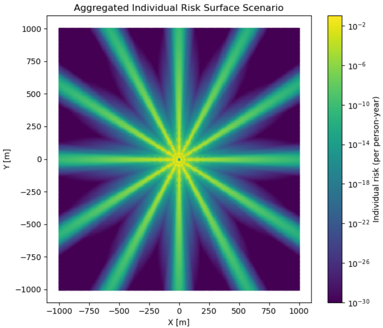
- Uses discrete leak sizes and discrete weather conditions.
- Fixed scenario weights f_i.
- This method is essentially limited by how many scenarios a person can list.

Update (process based)

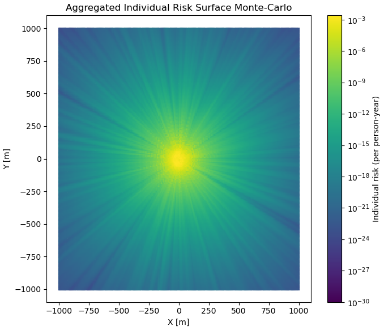
$$IR(s) \;=\; \frac{1}{t_1 - t_0} \int_{t_0}^{t_1} \mathbb{E}\big[D_t(s) \,\big|\, \Delta N_t = 1\big] \, \lambda_t \, dt$$

- Intensity λ_t multiplied by the lethality over time.
- Direct sampling of time and weather.
- Can simulate as many samples ($\approx$scenarios) as computer allows.

Scenario vs. Monte Carlo: Individual risk contours



Scenario method



Monte Carlo method

- **Temporal aggregation:** compute consequences for each realization to obtain true temporal average risk.
- **No need for spatial smearing:** to account for only a few wind directions, it is typical to widen the leak spread to 30.

Modularity and efficiency

- **Data requirements:** use measured weather directly as samples, not hand made scenarios.
- **Automation:** simulations run automatically over time and samples, reducing manual work.
- **Modularity:** the framework is modular, you can replace the dispersion or lethality model without changing the rest of the analysis.

Conclusions

- **Rigorous foundations:** Probability theory clarifies QRA assumptions and enables full stochastic models.
- **Improved spatial detail:** Full Monte Carlo simulation improves spatial detail.
- **Practical feasibility:** Simulations over each hour in a year are computationally feasible.
- **Policy relevance:** More realistic estimates help avoid the danger of underestimating risk and the costs of overestimating.

Outlook

- **Stochastic calculus:** draw more inspiration from risk-assessment fields such as finance, where the theory is more developed.
- **Advanced dispersion models:** incorporate computational fluid dynamics (CFD) with AI surrogates to improve dispersion modelling and speed.
- **Broad applicability:** apply the framework to nuclear Level 3 probabilistic safety assessments (PSAs), the transport of hazardous materials, and environmental hazards.

Thank you for listening!

Questions?