Considerations on scenario analysis

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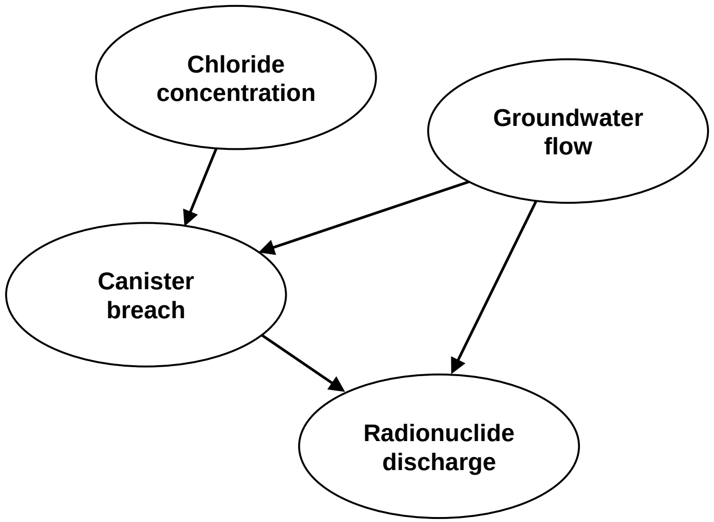
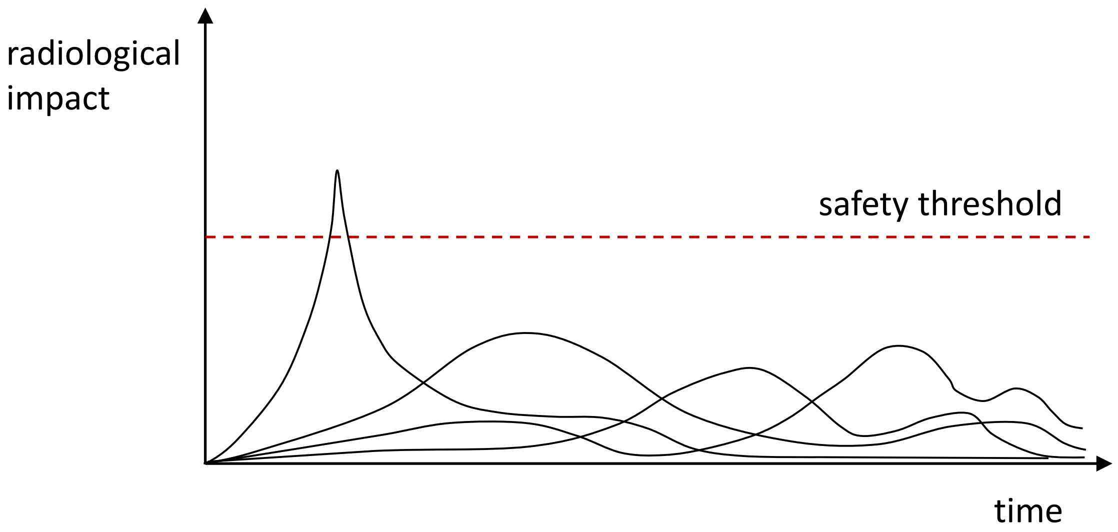
Background & motivation

- Decisions on safety-critical systems are informed by risk assessments
- System evolution is uncertain
- Uncertainty is often addressed by scenario analysis
    - FEP identification
    - System model
    - Scenario generation
    - Consequence analysis

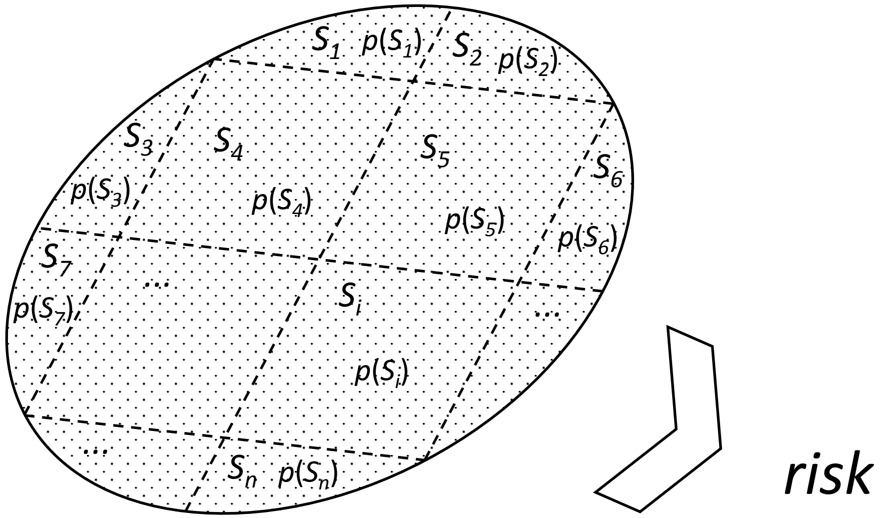


Approaches to scenario generation

- Pluralistic approach
  - representative scenarios are formulated by expert judgment

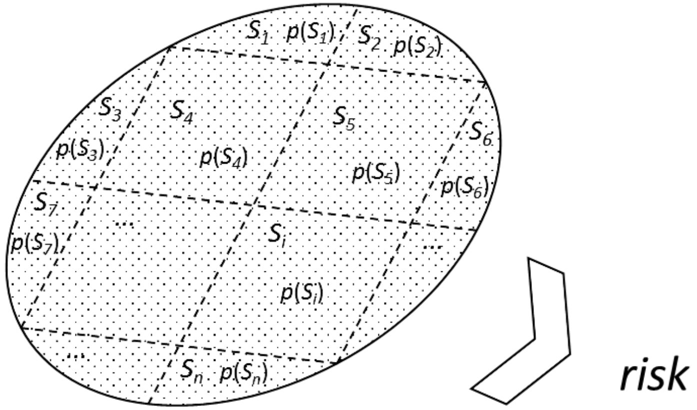


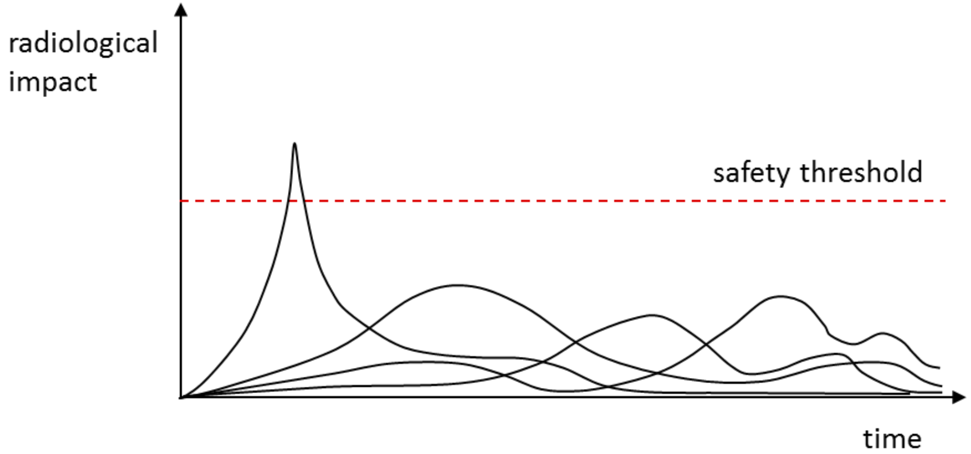
- Probabilistic approach
  - the possible system evolutions are modeled by a probability space



Arguments

- Objections to probabilistic approaches:
  - they lack transparency
  - risk estimates are misleading (FEP uncertainty)
  - `` Where do you get the probabilities? ´´
- Objections to pluralistic approaches:
  - they still make implicit probabilistic claims
  - additonal scenarios can lead to violation





Comprehensiveness

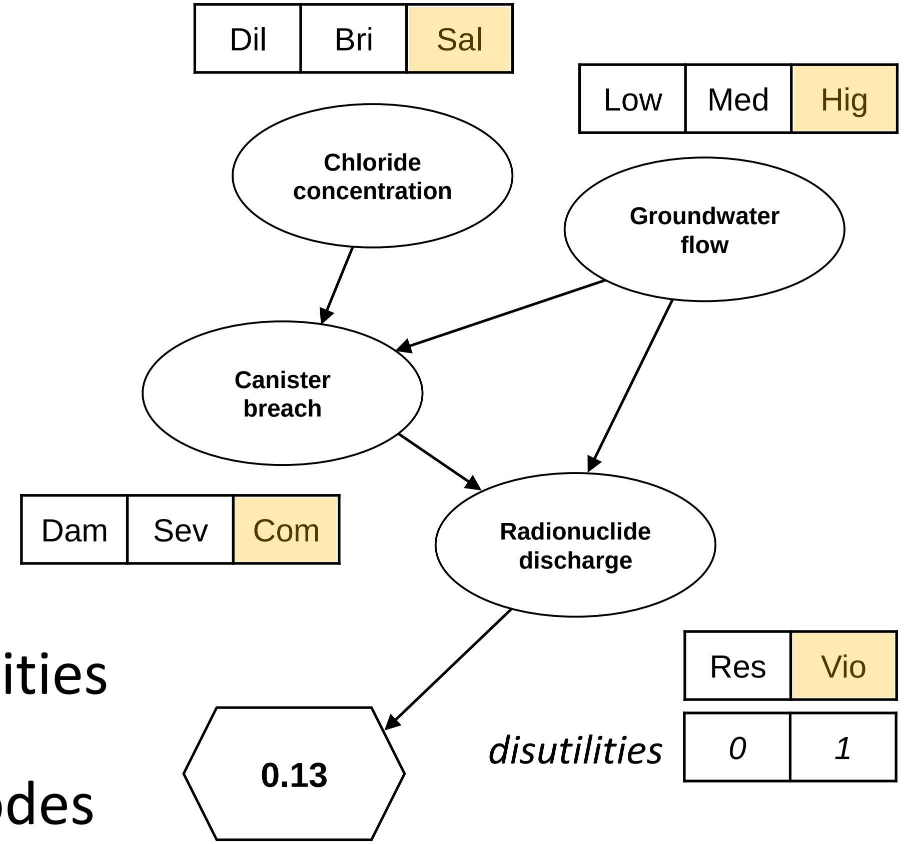
- In FEP identification
  - all *significant* FEPs are identified
- In scenario generation, interpretations are approach-dependent
  - pluralistic → the scenarios are *representative* of the possible system evolutions
  - probabilistic → the probability space is widely explored
- Here, the focus is on comprehensiveness in scenario generation

Interpreting comprehensiveness

- Scenario analysis inevitably leaves residual uncertainty about risk, due to
  - the impossibility of simulating the infinite number of system evolutions
  - the *epistemic* uncertainties in the information (e.g., model parameters)
- *Comprehensiveness is achieved if residual uncertainty is sufficiently small to assess conclusively whether the repository is safe or not*
- Quantifing residual uncertainty is the key to evaluating comprehensiveness
- Probabilistic approaches can be more readily validated

Bayesian networks

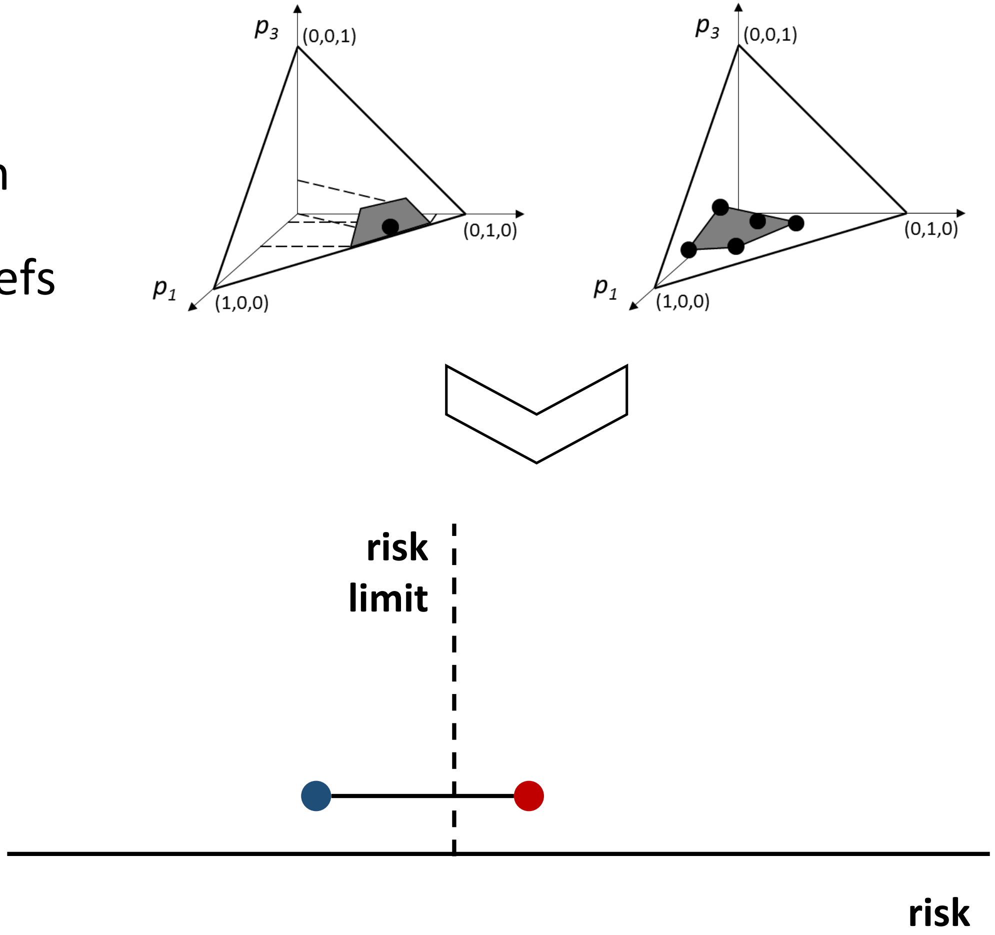
- The FEPs and the safety target are represented as nodes with discrete states
- State probabilities can be obtained by
  - computer simulations
  - expert judgments
- The safety target(s') states are associated with disutilities
- A *scenario* (path) *s* is a combination of states of all nodes
- Risk is evaluated as the expected disutility



$$E[U] = \sum_{s \in S} p(s)\ u(s)$$

Epistemic uncertainty & imprecise probabilities

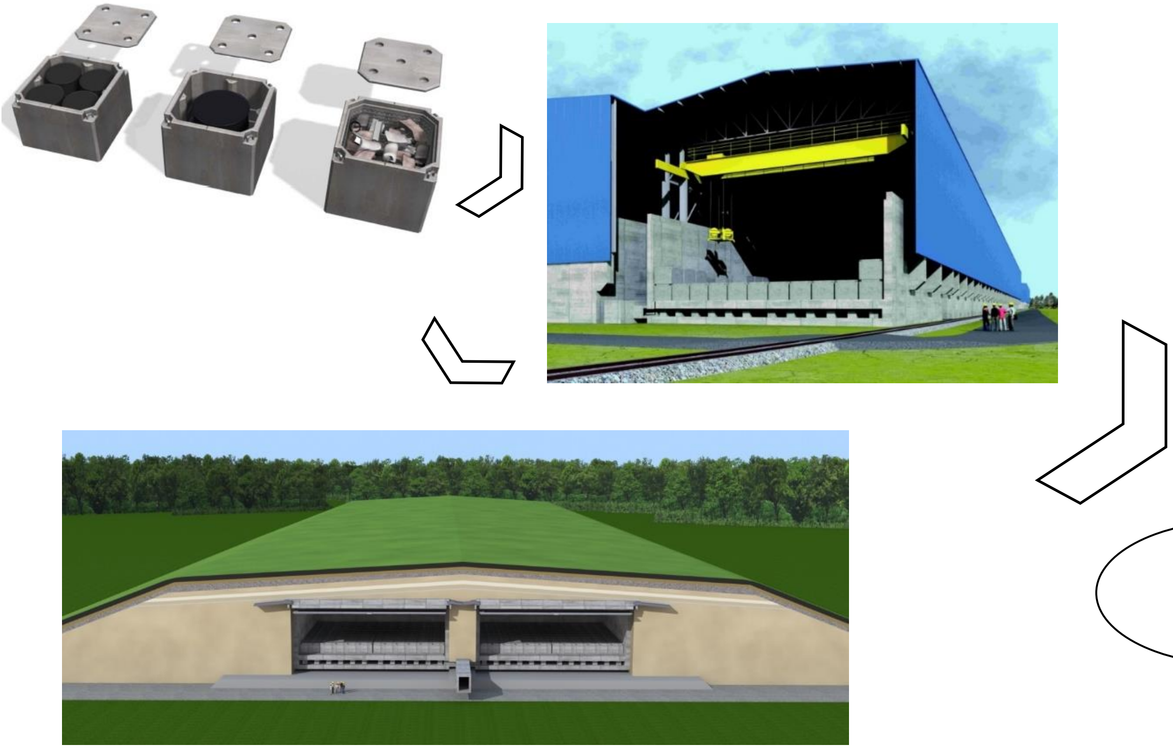
- It is hard to obtain precise probability values
  - computer simulations → model parameters, discretization
  - expert judgment → diversity among the experts' beliefs
- Point estimates are replaced with regions of feasible probability values
- Feasible regions are propagated to obtain a risk interval (quantifying residual uncertainty)
- *<u>Comprehensiveness is achieved if the risk limit is outside the risk bounds</u>*

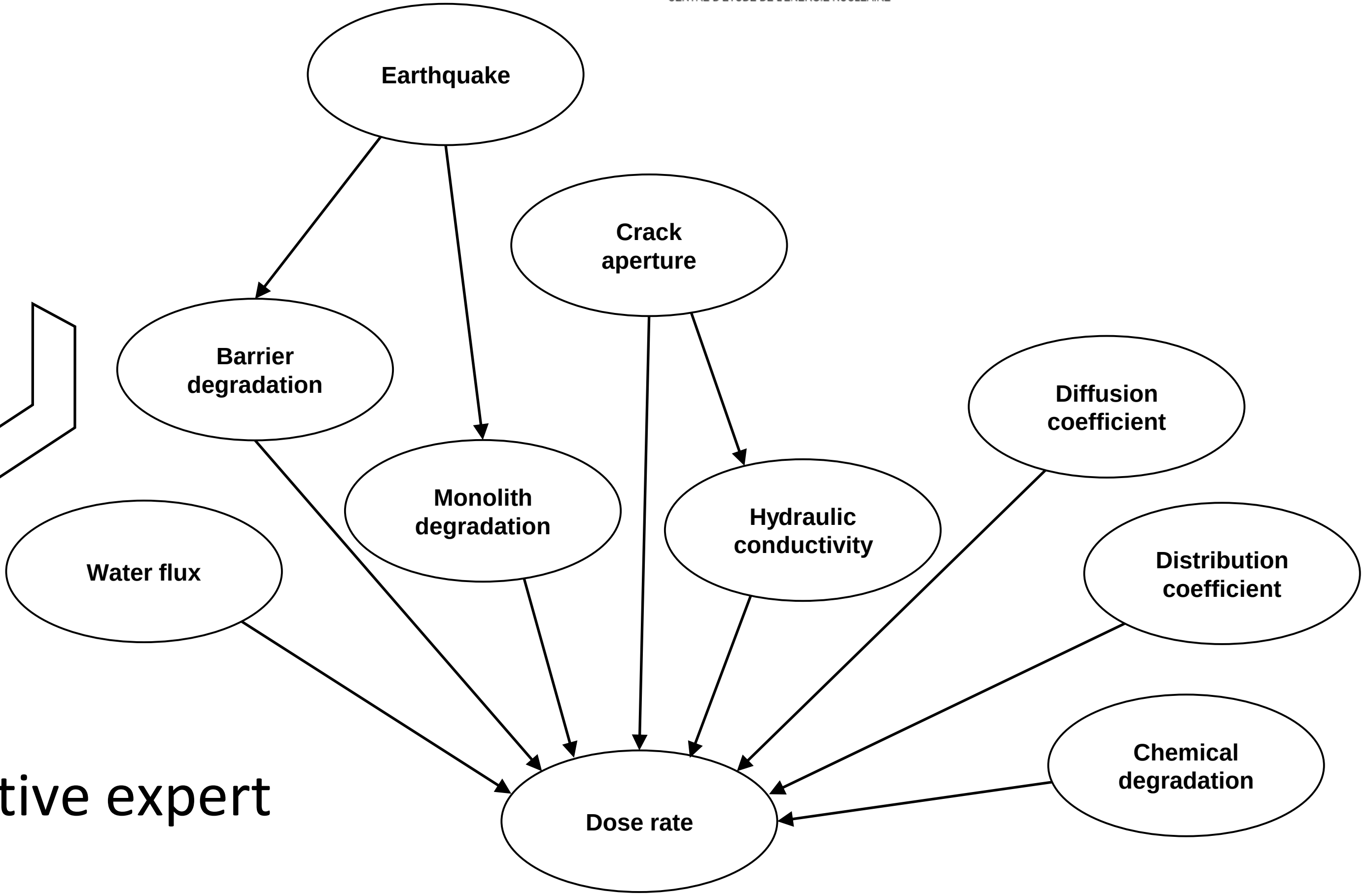


Safe? Unsafe? Comprehensiveness not achieved

Dessel case study – the model

- A Bayesian network for a near-surface repository is built with the SCK•CEN

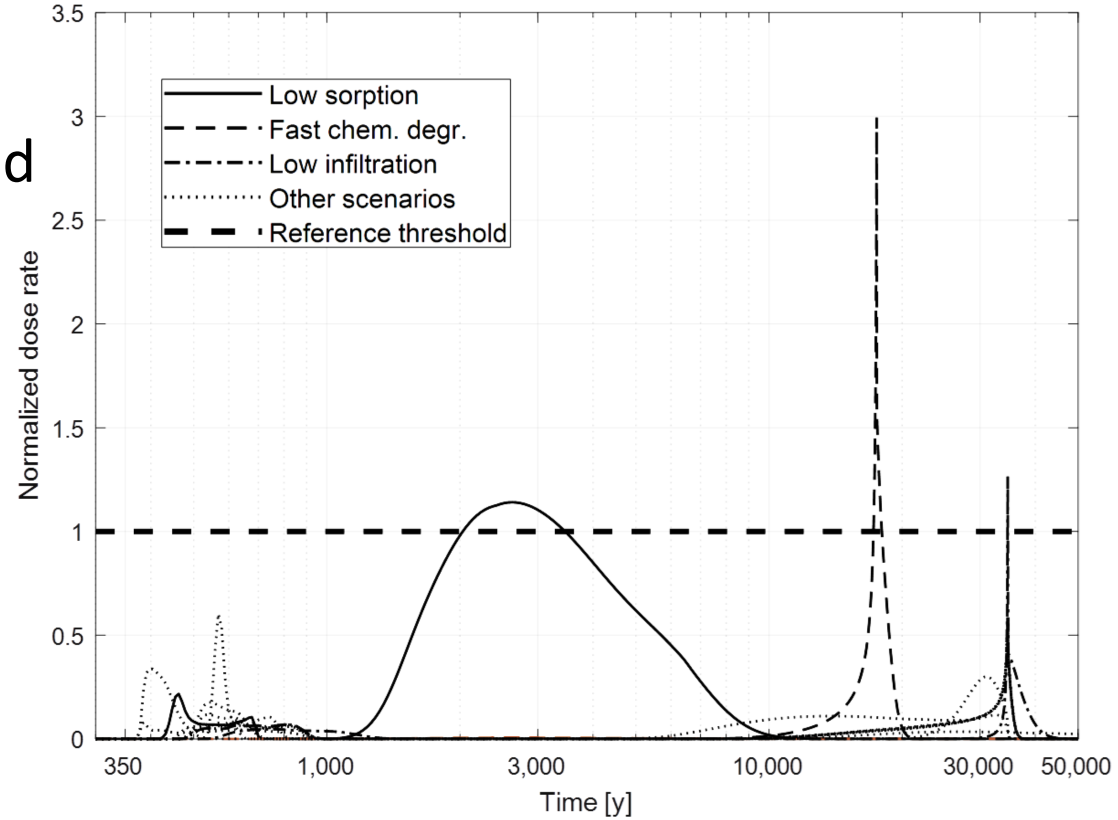




- Probabilities are estimated from illustrative expert judgments and *1,000* COMSOL simulations

Dessel case study – results

- The resulting risk interval is [*0.03* – *0.86*]
- Comprehensiveness may not have been achieved
  - more simulations should be run
  - a larger degree of consensus between experts should be sought
- A pluralistic analysis is also performed by simulating *13* representative scenarios



- Only probabilistic approaches make it possible to quantify residual uncertainty, evaluate comprehensiveness, and help pursue it efficiently

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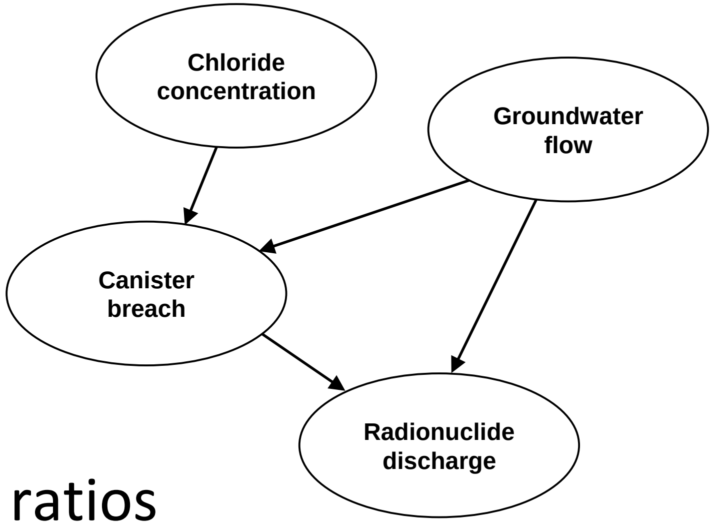
Epistemic uncertainty & cross-impact analysis

- Expert judgments can also be elicited about the dependencies
- Cross-impact statements are revisited probabilistically:

$$C_{kl}^{ij} = \frac{p_{k|l}^{i|j}}{p_k^i}$$

〉 *How much more (or less) likely is FEP i to be in state k, if FEP j is in state l ?*

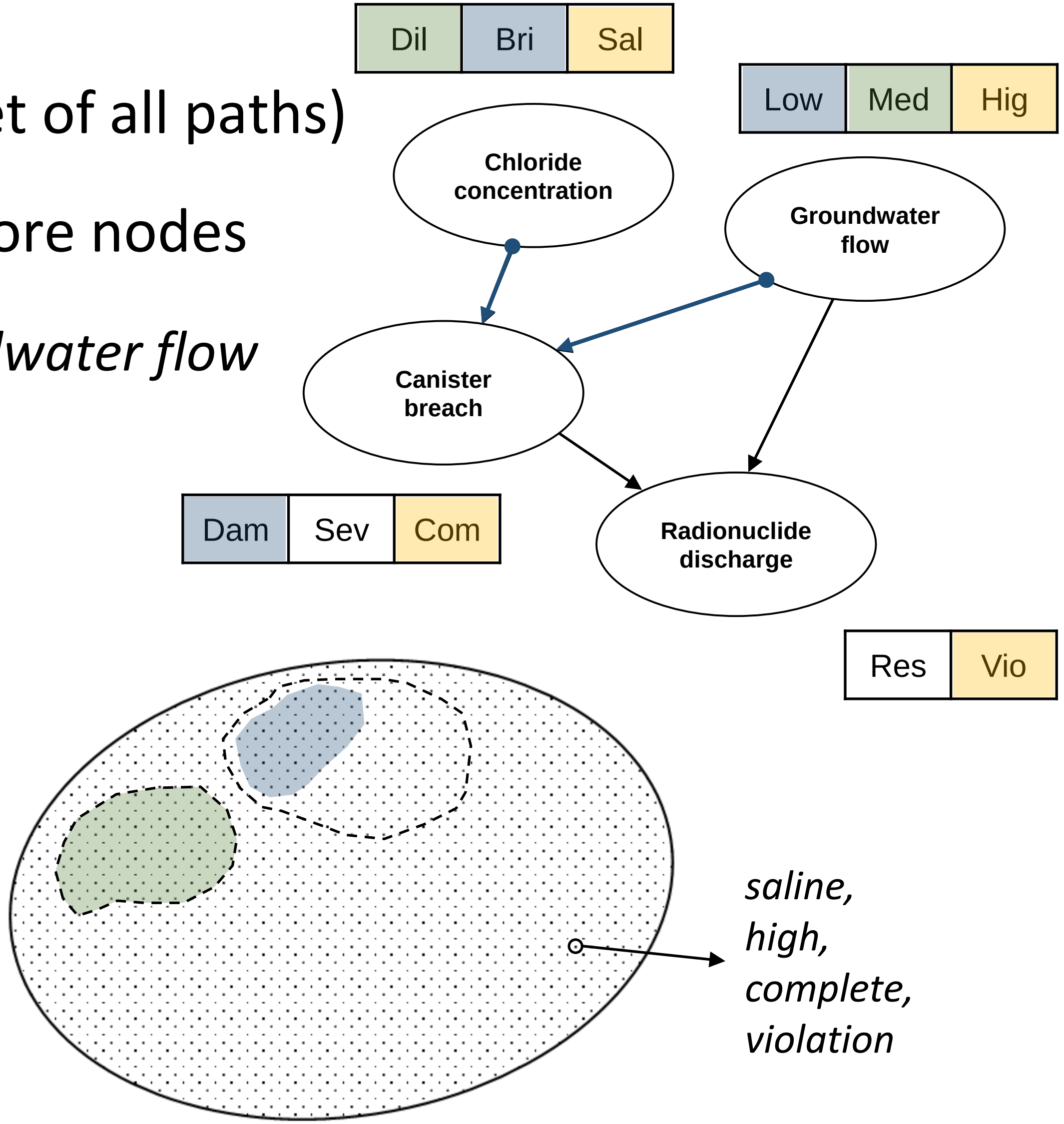


- Epistemic uncertainties imply bounds for the cross-impact ratios
- Together with bounds on the disutilities, these bounds can be propagated to estimate a risk interval

$$E[U] = \sum_{s \in S} p(s)\ u(s)$$

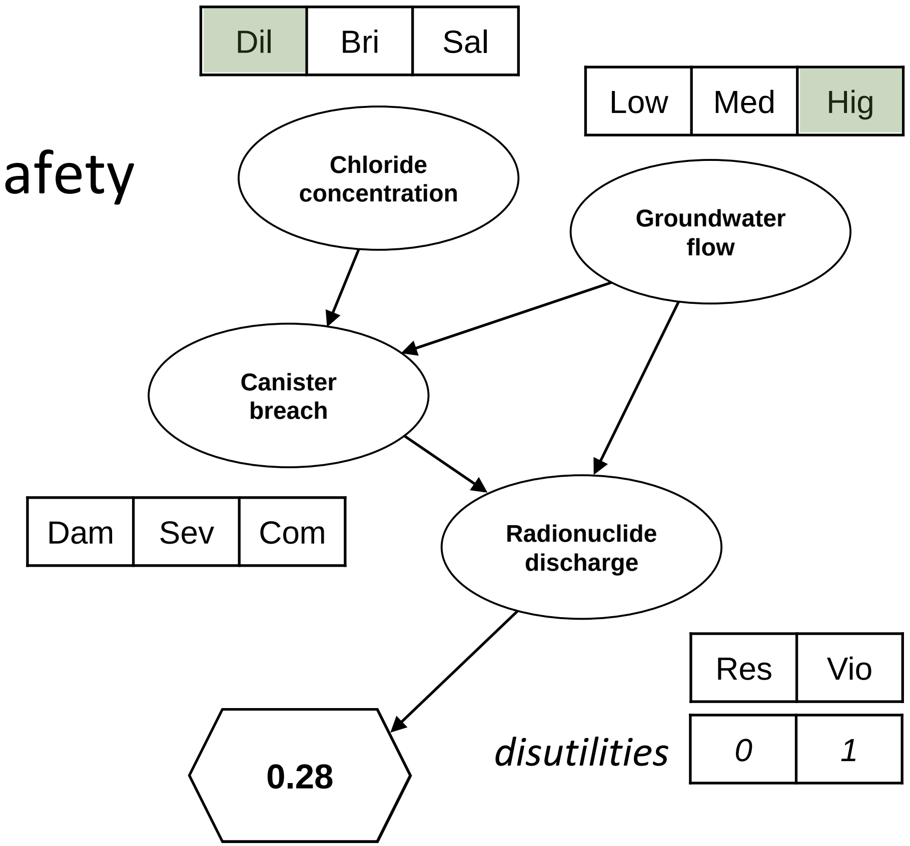
Scenarios

- A scenario is a collection of paths (subset of the set of all paths)
- *Projected* scenarios specify the *states* of one or more nodes
  - e.g. *dilute chloride concentration*, *medium groundwater flow*
- *Causal* scenarios specify the states of one or more nodes, *depending* on the states of others
  - e.g. if *chloride concentration* and *groundwater flow* are *brine* and *low*, *canister breach* is *damage*



Risk importance measures

- Conventional risk importance measures quantify the impact of a given component’s performance on the safety of the overall system
- However, conventional risk importance measures
  - require the definition of component failure
  - focus on individual components
  - are restricted to the binary evaluation of safety
- Here, risk importance measures are extended to scenarios



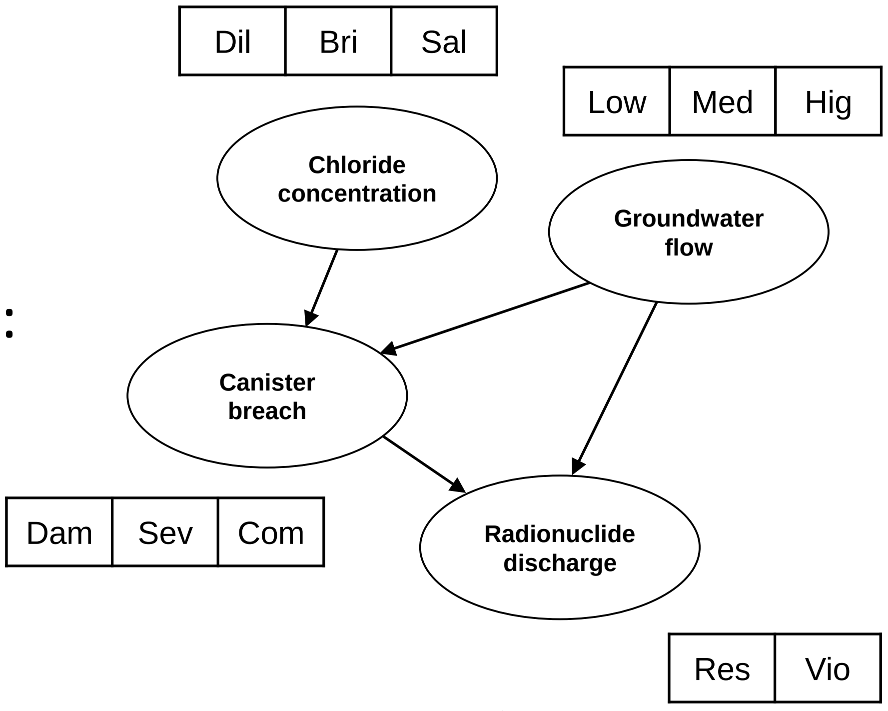
Extension to scenarios

- Risk achievement worth (RAW) → *Relative risk change if the scenario occurs*
- Risk reduction worth (RRW) → *Relative risk change if the scenario does not occur*
- Birnbaum importance (BI) → *Risk difference if the scenario occurs or not*
- Criticality index (CI) → *Marginal risk difference if the scenario occurs or not*
- Risk share (RS) → *Share of overall risk contributed by the scenario*
- All measures identify the *risky* scenarios consistently

$$E[U|S] > E[U] \leftrightarrow RAW(S) > 1 \leftrightarrow RRW(S) > 1 \leftrightarrow BI(S) > 0 \leftrightarrow CI(S) > 0 \leftrightarrow RS(S) > p(S)$$

Finding the riskiest scenarios

- The number of scenarios can be very large
- Explicit enumeration may not be possible
- The riskiest scenarios are determined by optimization:
  - objective function
    - → *expression of the selected risk measure*
  - variables
    - → *binary ones to include/exclude paths in/from the scenario*
  - constraints
    - → *specific FEPS and/or scenario types; scenario ranking*

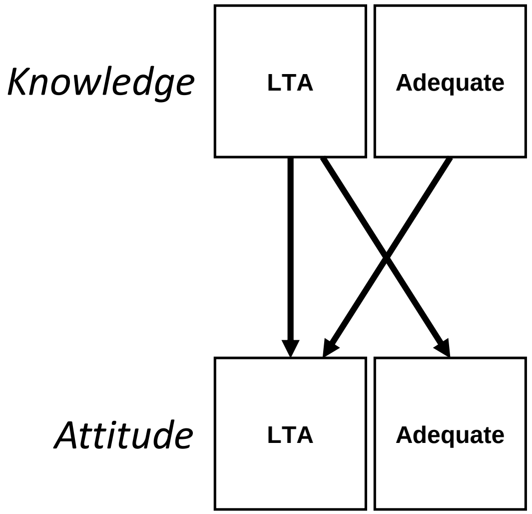


54 paths

$2^{54} - 2 \approx$ 20 millions of billions of scenarios

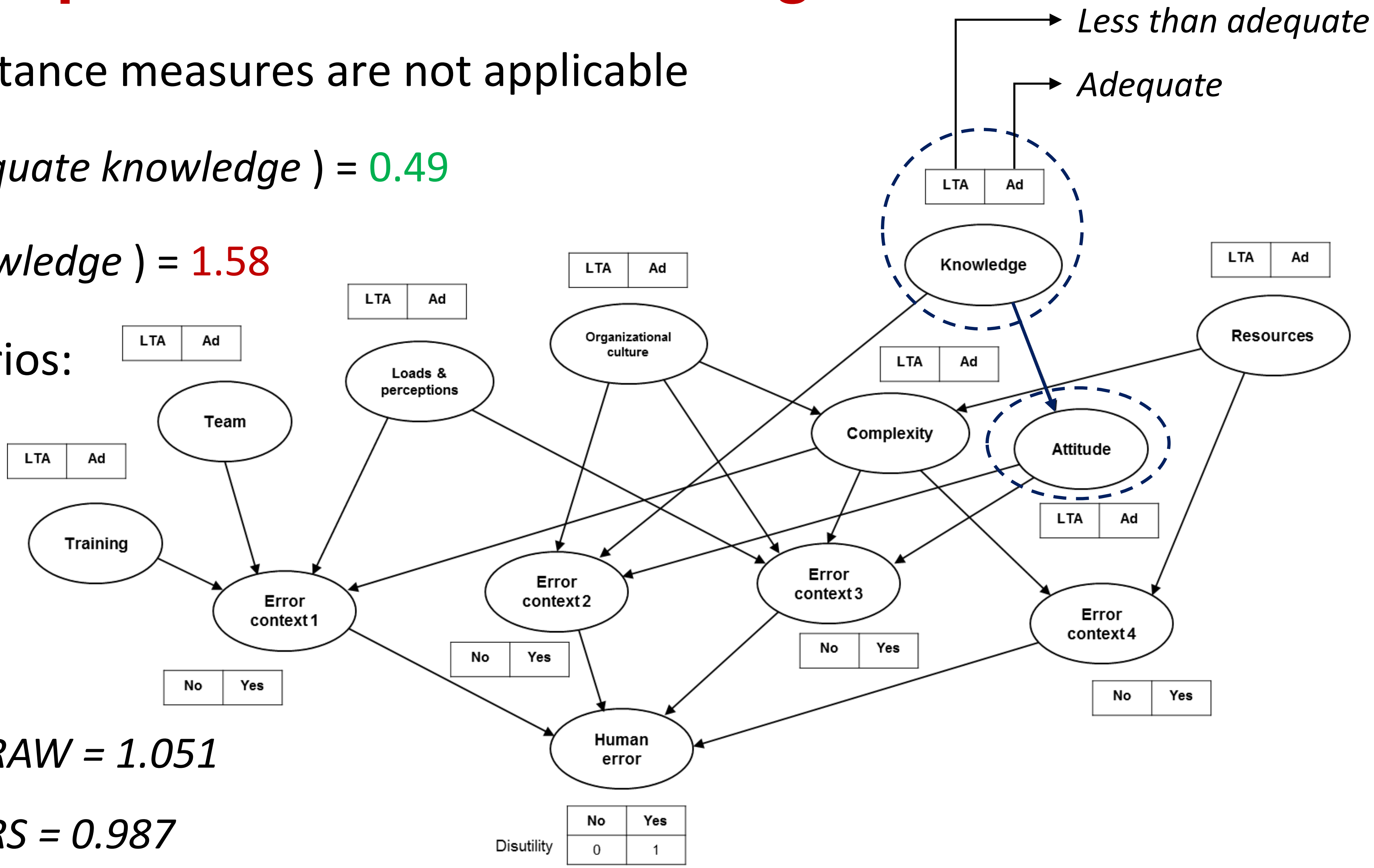
Human errors in spent-nuclear-fuel storage

- Conventional risk importance measures are not applicable
  - RAW (*Less than adequate knowledge*) = 0.49
  - RAW (*Adequate knowledge*) = 1.58
- Examining causal scenarios:



RAW = 1.051

RS = 0.987



Takeaways

Characterize the uncertainties

Ensure transparency

- Distiguish between FEP identification and scenario generation
- Quantify residual uncertainty about risk
- Adopt probabilistic approaches
- Build a system model
- Identify the riskiest scenarios

Evaluate comprehensiveness