PRAMEA – probabilistic risk assessment (PRA) methods and applications

Presentation at the SAFIR2018 Interim Seminar

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Project overview

- PRAMEA is an umbrella project covering most of PRA
  - not included: some aspect of digitalized control system PRA, applied PRA in risk-informed in-service inspections of pipes
- Main objectives
  - Improve and develop methods for risk-informed decision making
  - Improve and develop PRA methods
  - Develop PRA knowledge and expertise in Finland
  - Foster international cooperation, import best practices to Finland
- Not included in this presentation
  - Use of human reliability analysis (HRA) outside of PRA
  - Dynamic PRA (analysis of dynamic flowgraph methodology)
  - Importance measures for operations involving schedule risks

Human Reliability Analysis (HRA) for advanced control rooms (ACR)

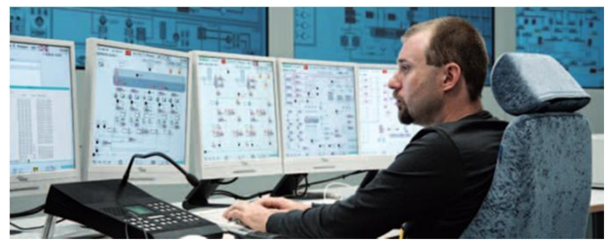
- The use of digital human-system interfaces (HSI)
    - Changes the working environment of the operator
    - Induces new tasks
    - Modifies the group dynamics and communication.
- Suggested effects on human reliability:
    - Improved crew performance and reduced workload
    - Declined primary task performance due to attention shift to interface management
    - Sub-optimal use of the HSI in high workload situations due to minimized capability to focus on interface management tasks
- Traditional HRA methods cannot properly address the new aspects introduced by digital HSI

Source: TVO

Analogue conventional control room

- Paper-based procedures
- Hard-wired indicators/LCD displays
- Hard-wired/Analogue controls

Source: TVO



Digitalised advanced control room

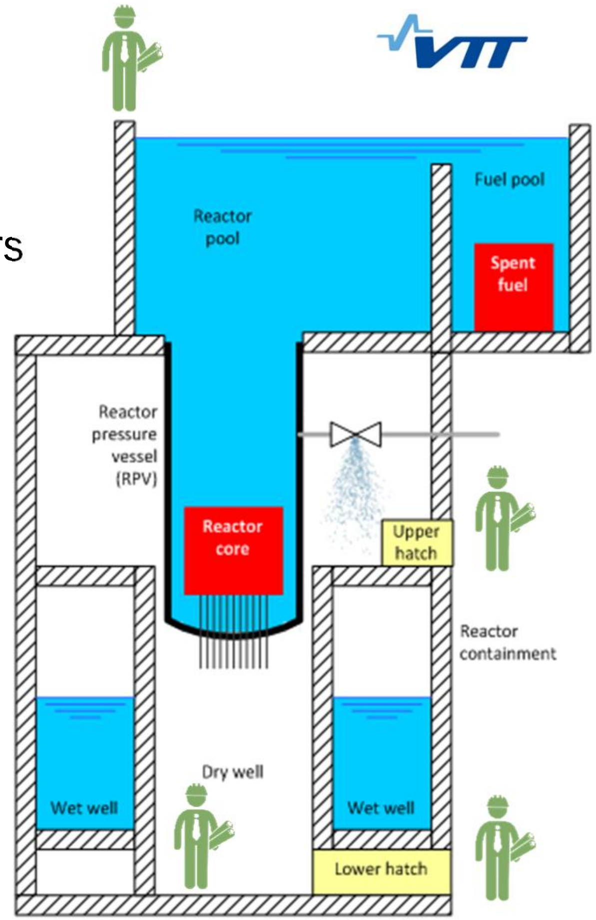
- Computer-based procedures
- Integrated information system
- Soft controls

Human Reliability Analysis (HRA) for advanced control rooms (ACR) - Results

- Literature review
  - The effect of digital HSI on human behavior and reliability
  - Applicability of traditional HRA methods to digital HSI
  - HRA methods for digital HSI
  - U.S.NRC NUREG guidelines
- Analysis of performance shaping factors (PSF)
  - Appropriateness of commonly used PSFs in ACR settings
  - Human factor issues affecting performance in ACR
  - Overview of ways to assess effect of PSFs
- Safety benefit:
  - Better modelling of human reliability in ACR
  - Enables identification of safety weaknesses in ACR settings

Assessment of dependences in human reliability analysis (HRA)

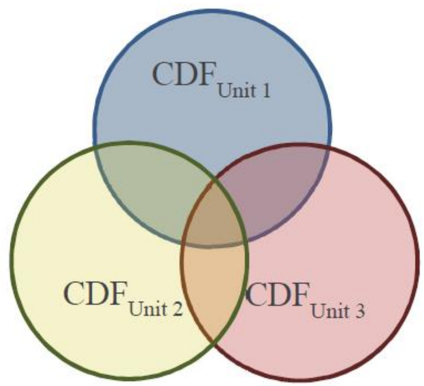
- Many PRA scenarios include multiple human interactions
- Literature and case studies have been performed to summarise the state-of-the-art and to provide recommendations for PRA practitioners
  - Finnish-Swedish collaboration
- First issue is to identify relevant dependences, e.g.
  - testing or maintenance of redundant equipment
  - multiple operator actions during accident scenario
- For quantification, tabulated values/formulas can be used:
  - No – Low – Medium – High – Full dependency
- Safety benefit: identification of potential human factors weaknesses at the plant, more realistic risk assessment



Example: LOCA during refuelling outage

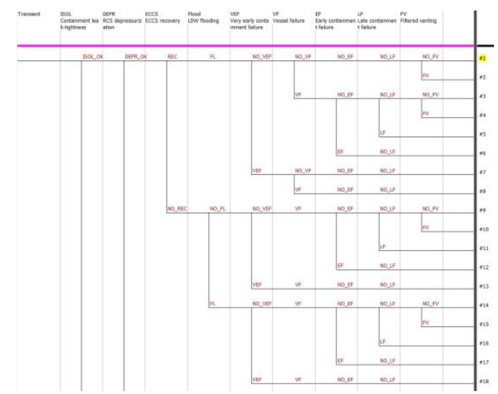
Multi-unit PRA

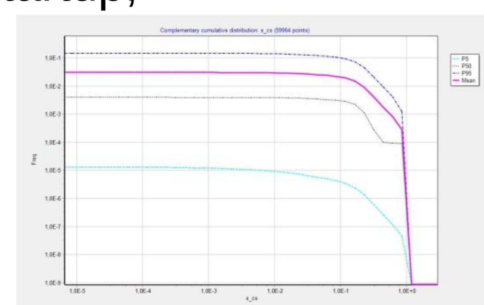
- Previously PRA has only been performed for individual reactor units even though there are dependencies between the units
- A multi-unit PRA methodology has been outlined
  - Aims to estimate multi-unit core damage frequencies (or large early release frequencies) related to different multi-unit dependencies
  - Quantitative analysis aims to utilize existing single unit PRA models as much as possible
  - Identification, analysis, modelling and quantification of multi-unit dependencies
- Risk metrics, and required input data and supporting analyses have been considered in the report
- Safety benefit:
  - Analysis of multi-unit risks



Level 2 PRA analyses: release height and temperature, hydrogen explosions

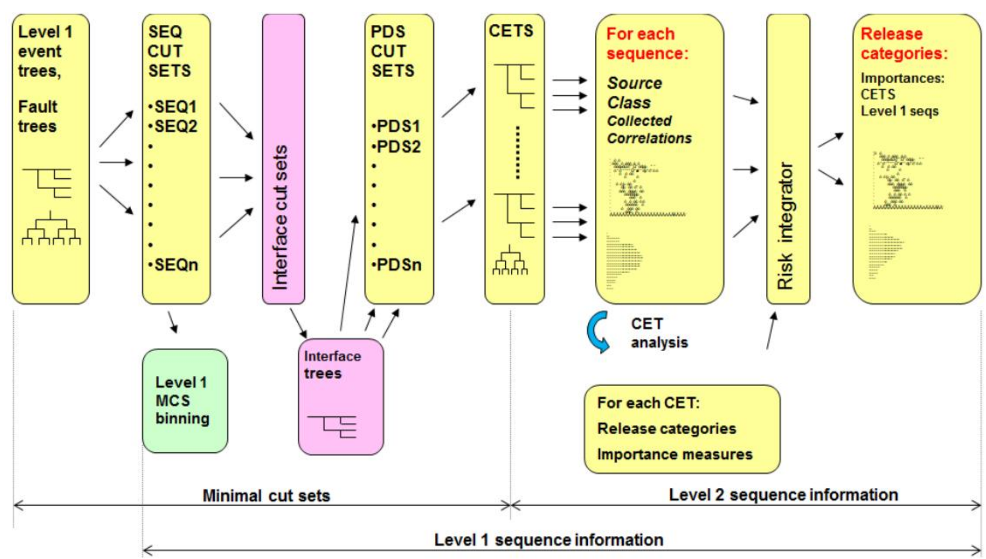
- Developed in the IDPSA framework
- Factors affecting containment release height and temperature identified
  - Height affected by containment failure mode
    - Mostly isolation failures through doors, cable penetrations etc.
  - Chimney height in controlled releases
  - Temperature normally close to 100°C
    - Fires and explosions may rise T
- Hydrogen explosions studied
  - In BWR, may occur as a result of inerting failure, or during startup, shutdown or refuelling
- Safety significance: release height and temperature affect atmospheric dispersion





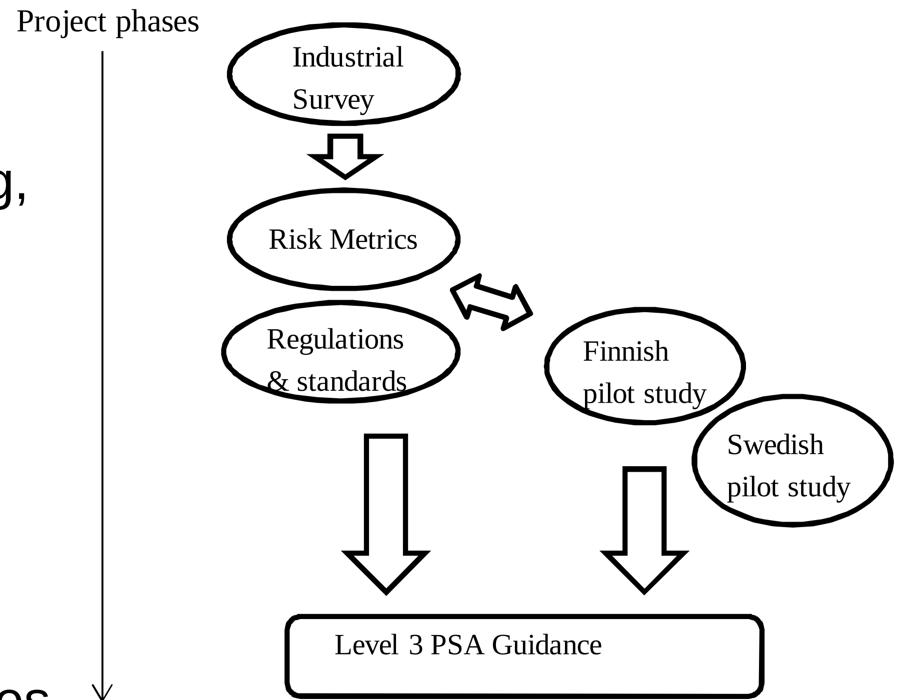
Level 2 PRA development: Tight integration between the levels 1 and 2

- PRA is most accurate when dependencies between levels 1 and 2 are modelled, and all the relevant information is passed from level 1 to level 2.
- Tight integration of PRA levels 1 and 2 was developed in FinPSA. The development focused on:
    1. How level 1 information is incorporated and utilised in level 2 models
    2. How level 1 accident sequences and basic events are seen in level 2 results
- FinPSA implementation is also verified and validated against Excel calculations.
- Safety benefit: More accurate level 2 results and improved trace back of level 2 results to level 1.

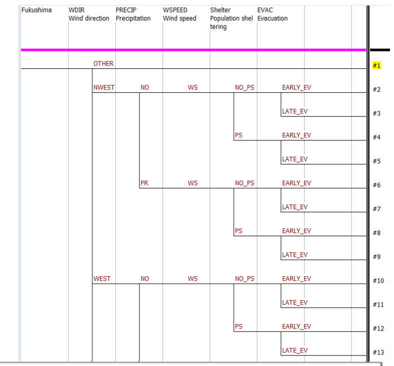


Nordic guidance for level 3 probabilistic safety assessment

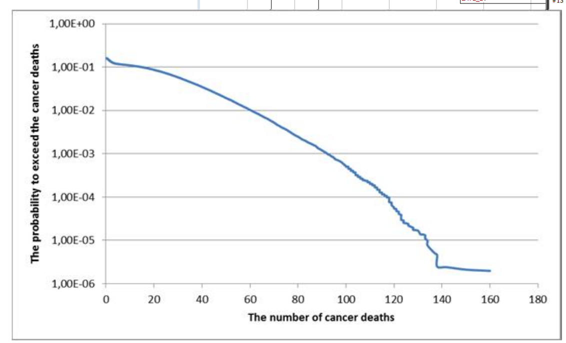
- Main result of a Nordic cooperation project
  - Partners: Lloyd's Register Consulting, ÅF consulting, Risk Pilot, VTT
- Main foci
  - Legal basis: Nordic regulatory framework
  - Standards, guidelines etc.
  - Risk metrics and safety criteria
  - Using data, handling countermeasures, presentation of results
- Main safety benefit: harmonization of analyses

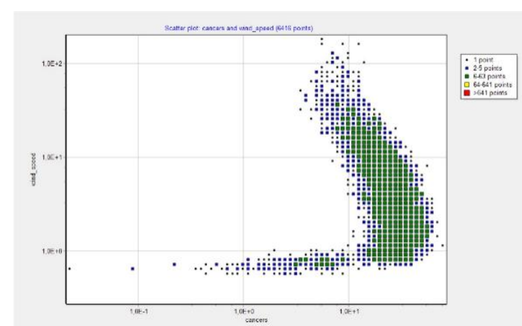


A pilot of using integrated deterministic and probabilistic safety assessment in level 3 PRA



- Problem: level 3 analyses are tedious
- Solution: combine deterministic and probabilistic analyses in a probabilistic model
- Implementation: probabilistic analyses in an event tree model (FinPSA), deterministic analyses with ARANO
- Safety benefits:
  - enables the conduct of extensive analyses with reasonable effort
  - provides a systematic risk picture





A review of dose assessment methods used recently

- Topic: population dose assessment methods used in major studies or modern software
  - VALMA, SILAM, RODOS, SOARCA study, UNSCEAR Fukushima study
- relatively little progress in last 20 years
- Safety analysis implications
  - Dose assessment could take human behaviour more accurately into account (behavioural simulation)
  - Dose assessment could be made physically more realistic (Monte Carlo simulation)
  - Dose assessment could use the result of more precise countermeasure analyses (traffic simulation in evacuation, structures of houses in shielding)

Portfolio Optimization for Risk-Informed Decisions

Aalto University

- Why portfolio optimization?
  - Prioritization based on standard risk-importance measures fails to account for costs
  - Component-based optimization leads to sub-optimal risk management plans
- Objectives
  - Develop methods for identifying combinations (portfolios) of risk management actions to minimize residual risks at different cost levels of risk management
  - Account for risk, cost of risk management and resource constraints simultaneously
  - Apply and evaluate methods to nuclear and other safety critical systems
- Challenges
  - Develop computationally tractable approaches for large systems
  - Using incomplete information when reliable parameter estimates are not available

Task 8.2: Achievements and future research

Completed applications

- Pipe inspections (c.f. RI-ISI)
  - Problem: Which pipes should be inspected, given incomplete information about failure probabilities and failure impacts ?
  - Large-scale optimization of inspections of the sewerage network in Espoo
- Defence-in-depth
  - Problem: Which combinations of safety barriers are cost-effective in a system with event dependencies and multi-state failure behaviours?
  - Ongoing collaboration with an Italian industrial partner with interests in barrier optimization for occupational safety (modelled through Safety Integrity Levels)

Future research

- Optimizing portfolios of testing strategies
- Applying methodologies with Finnish industrial partners
- Building and solving time-dependent Defense-In-Depth models

Journal publications

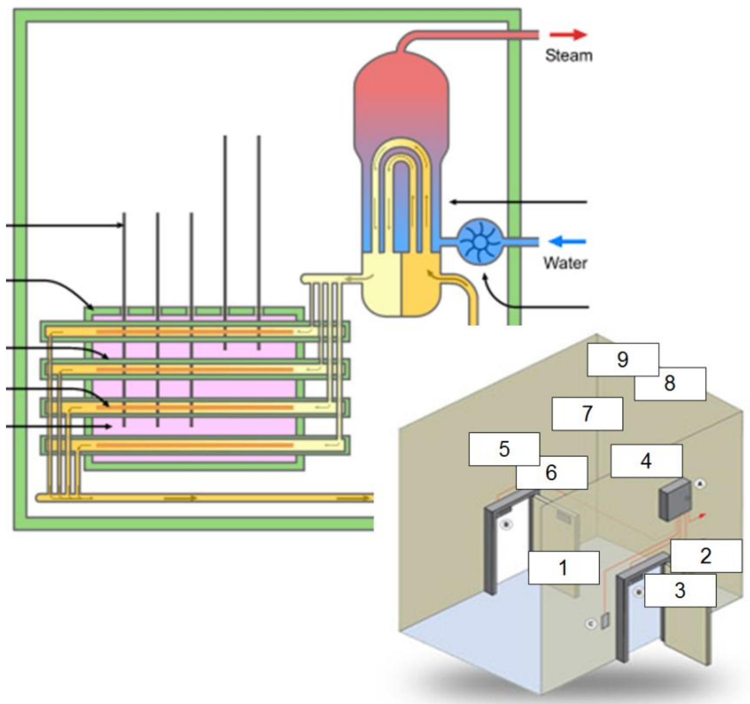
- A. Mancuso, M. Compare, A. Salo, E. Zio, T. Laakso, Risk based optimization of pipe inspections in large underground networks with imprecise information", *Reliability Engineering and System Safety* 152, pp. 228-238 (2016).
- A. Mancuso, M. Compare, A. Salo, E. Zio, "Portfolio optimization of safety actions for reducing risks in nuclear systems", conditionally accepted by *Reliability Engineering and System Safety* (2017).

Conference publications

- M. Compare, A. Mancuso, T. Laakso, A. Salo, E. Zio, "Identification of the most critical pipes in the presence of imprecise information", *Safety and Reliability of Complex Engineered Systems*, pp. 2717-2722, Taylor & Francis Group, London (2015).
- A. Mancuso, M. Compare, A. Salo, E. Zio, "Bayesian approach for safety barrier portfolio optimization", *Risk, Reliability and Safety: Innovating Theory and Practice*, pp. 1765-1772, Taylor & Francis Group, London (2016).
- A. Mancuso, M. Compare, A. Salo, E. Zio, "Risk informed decision making under incomplete information: Portfolio decision analysis and credal networks", to appear on ESREL conference proceedings (2017).

Application: CANDU airlock system

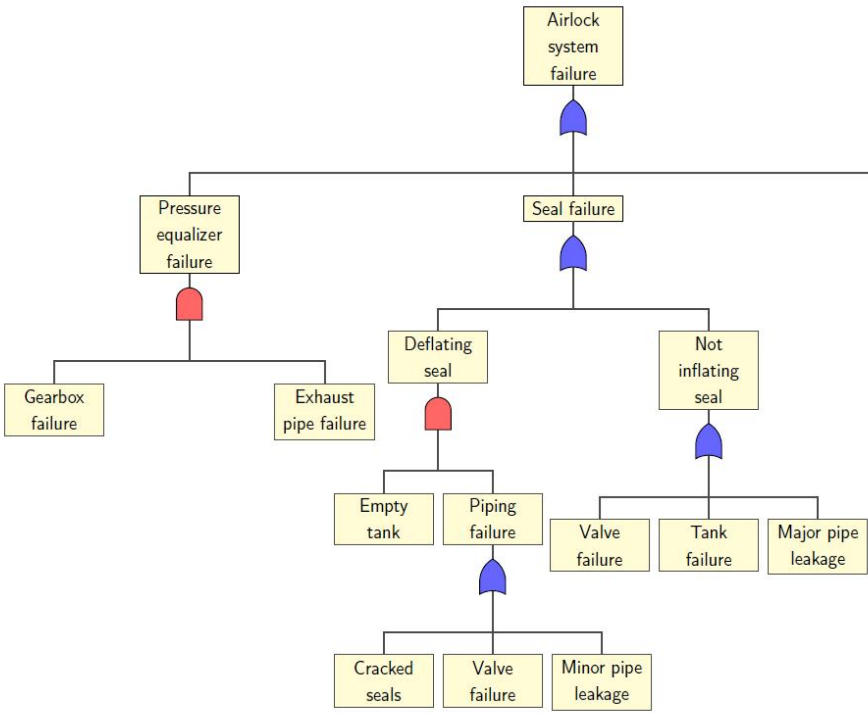
The Airlock System prevents the dispersion of contaminants by keeping the pressure of the inside of the reactor vault lower than the outside pressure.



	Basic Failure Events	ID Code
1	Pressure equalizer valve failure	V1
2	Doors failure	D1
3	Seal failure	S1
4	Gearbox failure	G1
5	Minor pipe leakages	P1
6	Major pipe leakages	P2
7	Exhaust pipe failure	E1
8	Empty tank	T1
9	Tank failure	T2

What **portfolios of risk management actions** minimize the residual system risk for the different total cost of risk management actions?

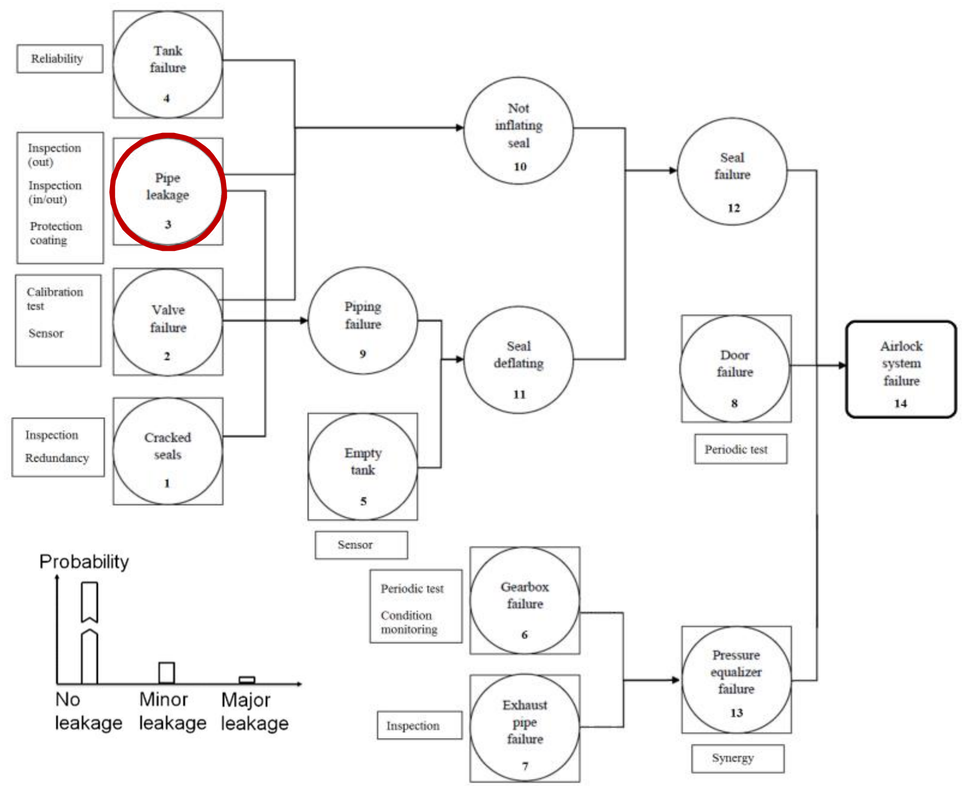
Approach



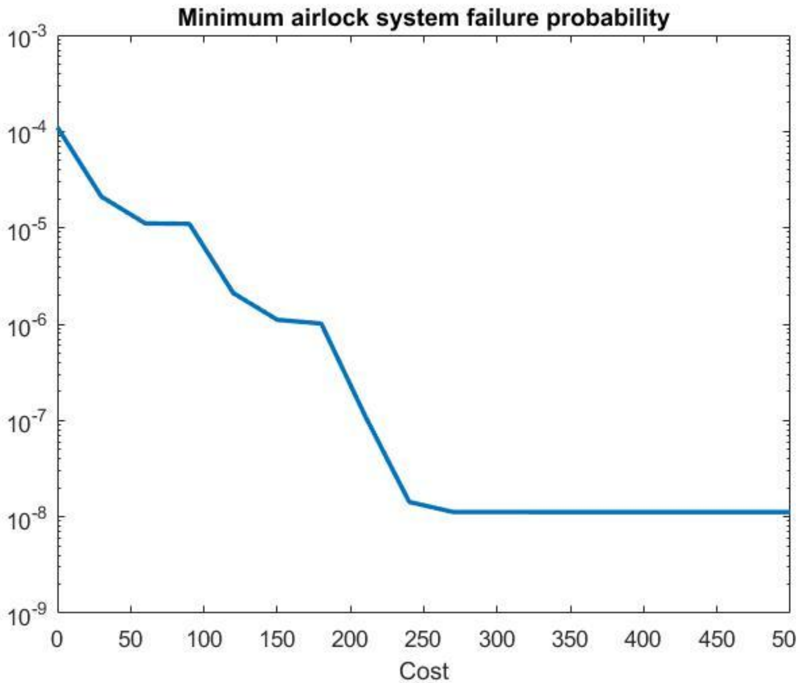
Advantages

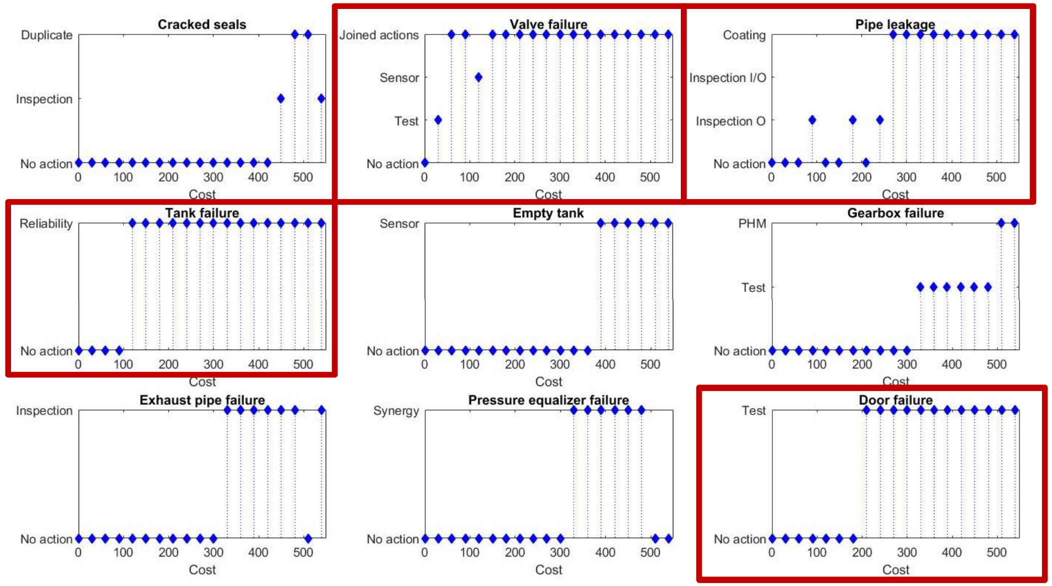
- Permits the modelling of multiples states
- Is a logical extension of AND/OR gates

- Convert the Fault Tree into a Bayesian network
- Formulate optimization problems for attaining safety targets (e.g., minimization of residual risk)
- Compute results with enumeration algorithms



Computational Results





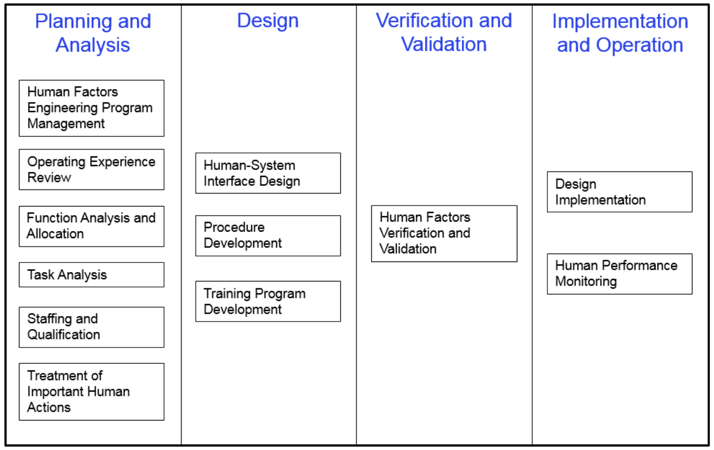
- Minimum airlock failure probability for the optimal portfolio of actions at different budget levels
- Larger budget
  $\Rightarrow$ more effective actions
  $\Rightarrow$ lower residual risk

- These portfolios are globally optimal in terms of minimizing the residual system risk
- This can give significant improvements over the traditional approach of selecting actions that target risky components one at a time

Application of Human Reliability Analysis outside of PRA context

- The aim is to find
  - how HRA has been used outside of PRA and
  - what potential HRA has to widen its scope in the nuclear domain

- 7 organisations responded to a questionnaire
  - FKA, RAB, ÅF, LRC, Fortum, STUK, TVO
- Presently, most use of HRA is PRA related
- Possible HRA applications
  - development of instructions
  - operator training
  - control room design (validation)
  - occurred events analysis
- Several difficulties in using HRA in a non-PRA context
  - limited resources, limited project budgets
  - cross-organizational activity
  - lack of guidance



Elements of the HFE program's review model (NUREG 0711 Rev. 3)

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