



International Conference on Probabilistic Safety Assessment and  
Management PSAM 14, September 2018, Los Angeles, CA.

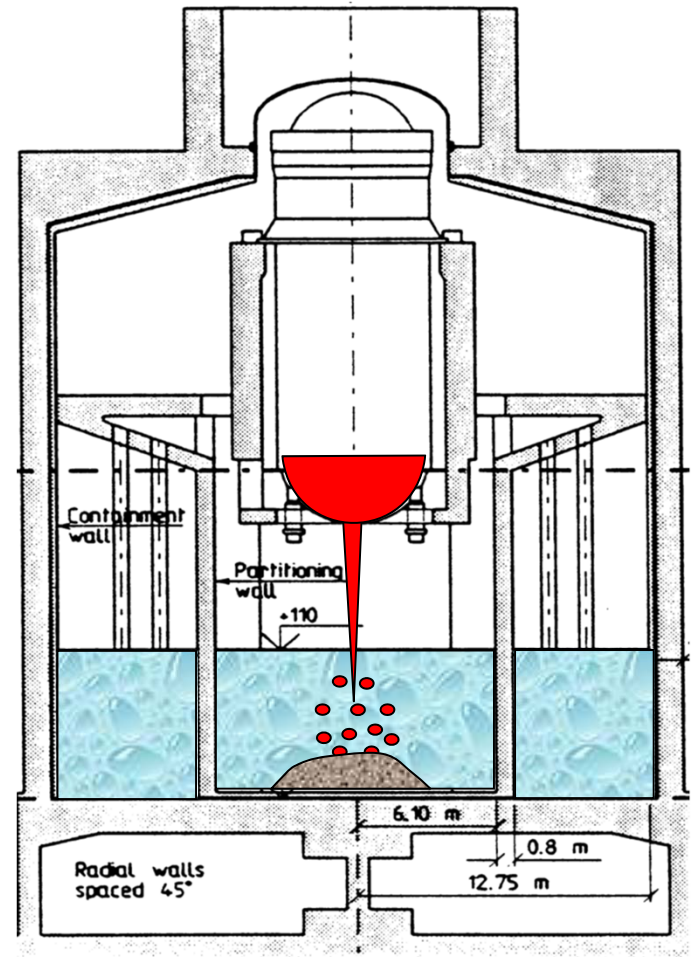
---

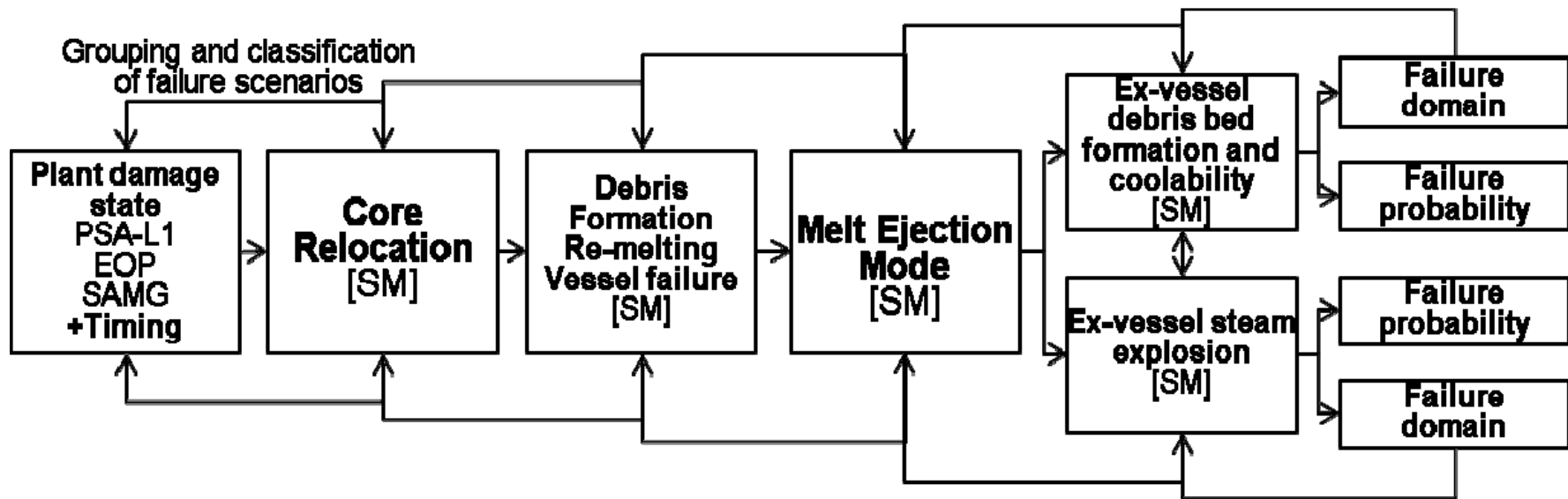
# **Risk Analysis Framework for Decision Support for Severe Accident Mitigation Strategy in Nordic BWR**

**Sergey Galushin,  
Dmitry Grishchenko, Pavel Kudinov**  
Royal Institute of Technology (KTH)  
Stockholm, Sweden

# Motivation: Nordic BWR Severe Accident

- **Severe accident mitigation strategy in Nordic BWRs:**
  - Lower drywell is flooded with water to **prevent cable penetrations failure** in the containment floor.
  - Core melt is released from the vessel into (7-12 m) deep water pool.
  - The melt is expected to fragment quench and form a **coolable debris bed**.
- **Threats to containment integrity**
  - Steam explosion.
  - Formation of non-coolable debris bed.
- depend on **melt release and pool conditions**.
- Melt release and pool conditions are affected by **the accident progression uncertainty:**
  - **Epistemic (phenomena)**
  - **Aleatory (scenarios)**.
- **Risk – uncertainty in effectiveness** of the strategy for preventing containment failure.





- **ROAAM+** framework is currently under development in KTH, for quantification of the conditional threats to containment integrity
- The ROAAM+ framework for Nordic BWR decomposes severe accident progression into a
  - set of connected causal relationships (CR)
  - Each CR is represented by respective surrogate model (SM)
    - Computational efficiency of the framework is necessary for extensive sensitivity and uncertainty analysis in forward (**failure probability**) and reverse (**failure domain**) analyses:



## Goals and tasks

---

- The ultimate goal of ROAAM+ application for Nordic BWR is to
  - provide a scrutable background in order to achieve convergence of experts' opinions in decision making:
    - Keep SAM strategy:
      - “Possibility” of containment failure is low even with “conservative” treatment of uncertainty, thus current strategy is reliable
        - » classical ROAAM, focus on “failure domain”: is it sufficiently small?.
    - Modify SAM strategy:
      - “Necessity” of containment failure in the course of accident is high
        - » i.e. “possibility” that containment doesn't fail is low even with “optimistic” treatment of uncertainty, thus the current strategy is unreliable and changes should be considered. Focus on “safety domain”: is it sufficiently large?
    - (Improve knowledge)
- Task:
  - Develop an approach for communication of ROAAM+ results.
  - Develop a decision support model.



## ROAAM+ Development of Knowledge Guided by Uncertainty Reduction

---

- The aim of ROAAM+ is to support decision making on the
  - risk acceptance, or
  - need for uncertainty reduction
    - additional data.
- Decision is robust if it is insensitive to uncertainty.
  - Uncertainty can be large.
- ROAAM+ framework is a tool for comprehensive uncertainty quantification, than enables us is to identify
  - **Main contributors** to the uncertainty in failure probability  $P_f$ .
  - **Importance** of the **dependencies** between different accident stages and respective models
    - in different accident progression scenarios.
  - The needs for **further refinement** of the knowledge:
    - Models / experiments / frameworks.

- Approach to risk assessment in ROAAM+



## Quantitative Definition of Risk

---

- The risk  $R_i$  associated with specific scenario  $s_i$  can be characterized by its frequency  $f_i$  and consequences  $c_i$ .
  - Consequences result from an assessment which is subject to uncertainty due to incomplete knowledge.
  - Such epistemic uncertainty (or degree of confidence) can be quantified as probability  $P_i$  (likelihood) of  $c_i$

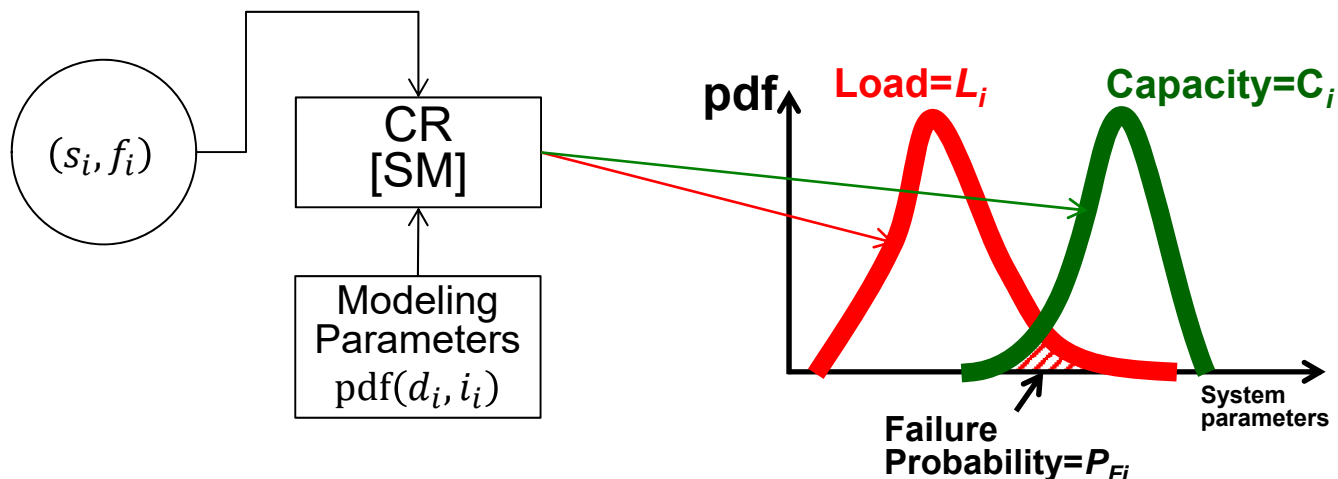
$$R_i = \{s_i, f_i, P_i(c_i)\} \quad (1)$$

- ***Separation of epistemic and aleatory*** uncertainties is one of the cornerstones of ROAAM.

# Failure probability

- For each plant damage state  $\{D_i\}$  there is a set of respective scenarios  $\{s_{ij}\}$  characterized by frequencies  $(f_{ij})$ .
  - **Scenarios ( $s_i$ ) define combinations of initial and boundary conditions for causal relationships (CR) and structure of the framework.**
- The CR provides assessment of the load ( $L_i$ ) and the capacity ( $C_i$ ).
  - **Epistemic uncertainty is introduced by multidimensional probability density function (pdf( $d_i, i_i$ )) of intangible ( $i_i$ ) and deterministic ( $d_i$ ) modeling parameters.**
  - **These distributions determine the probability of failure ( $P_{Fi} = P(L_i \geq C_i)$ ) in scenario ( $s_i$ ).**

$$P_{Fi} = P(L_i \geq C_i) = \iint_{L_i \geq C_i} \text{pdf}_{C_i L_i}(c, l) dc dl$$







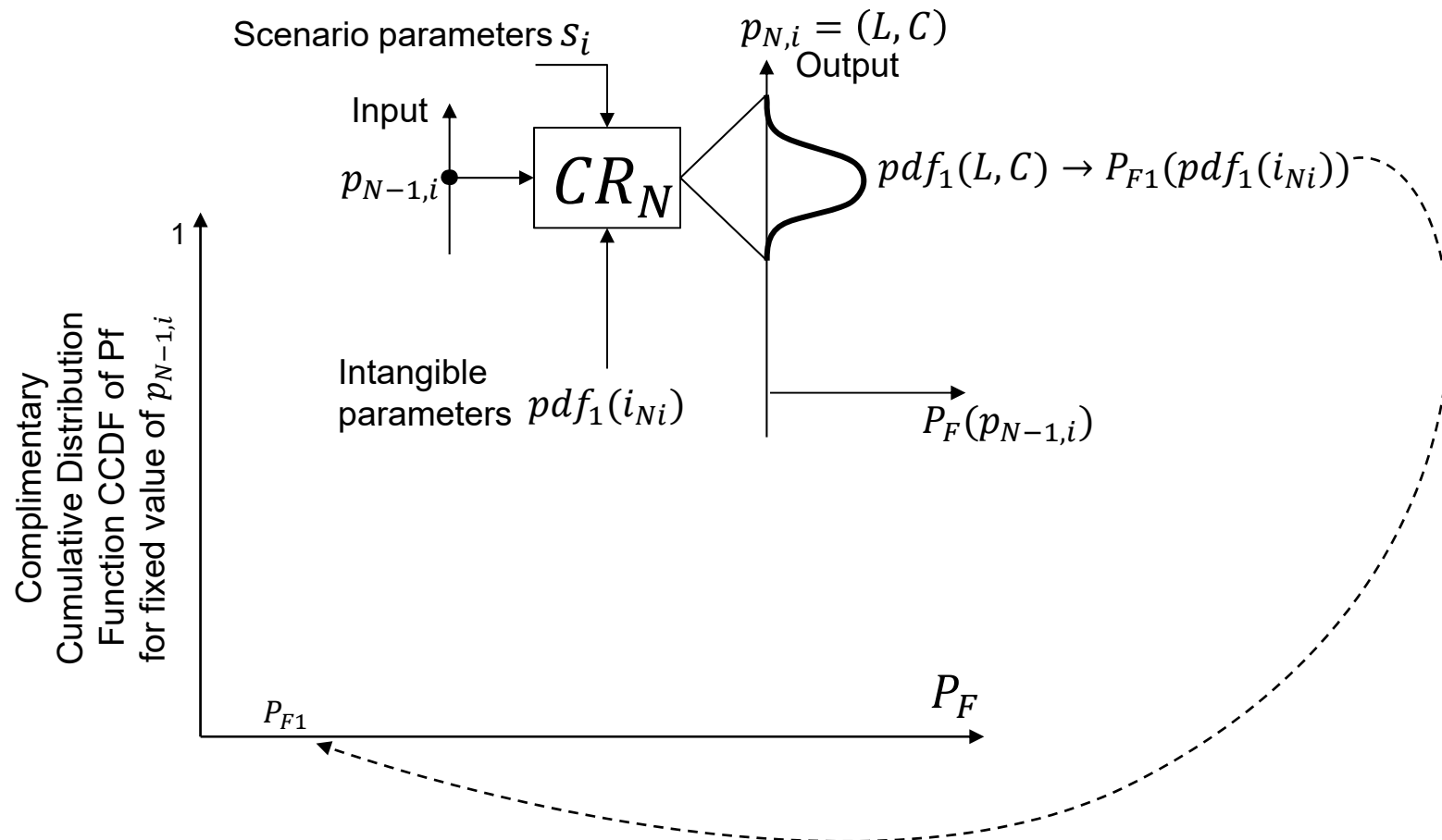
## Second Order Probability - ROAAM+

---

- In ROAAM+ framework for Nordic BWR we use the concept of second-order probability in quantification of conditional containment failure probability.
  - The need for the second-order probabilities comes from the nature of epistemic uncertainties in prediction of failure probability (i.e. partial probabilistic knowledge).
- Modelling (i.e. epistemic uncertain) parameters in ROAAM+ framework are separated into two groups:
  - Model deterministic parameters – complete probabilistic knowledge (i.e. range and probability distribution).
  - Model intangible parameters – partial probabilistic knowledge (i.e. one can only speculate regarding the possible range and expected type(s) of distribution).

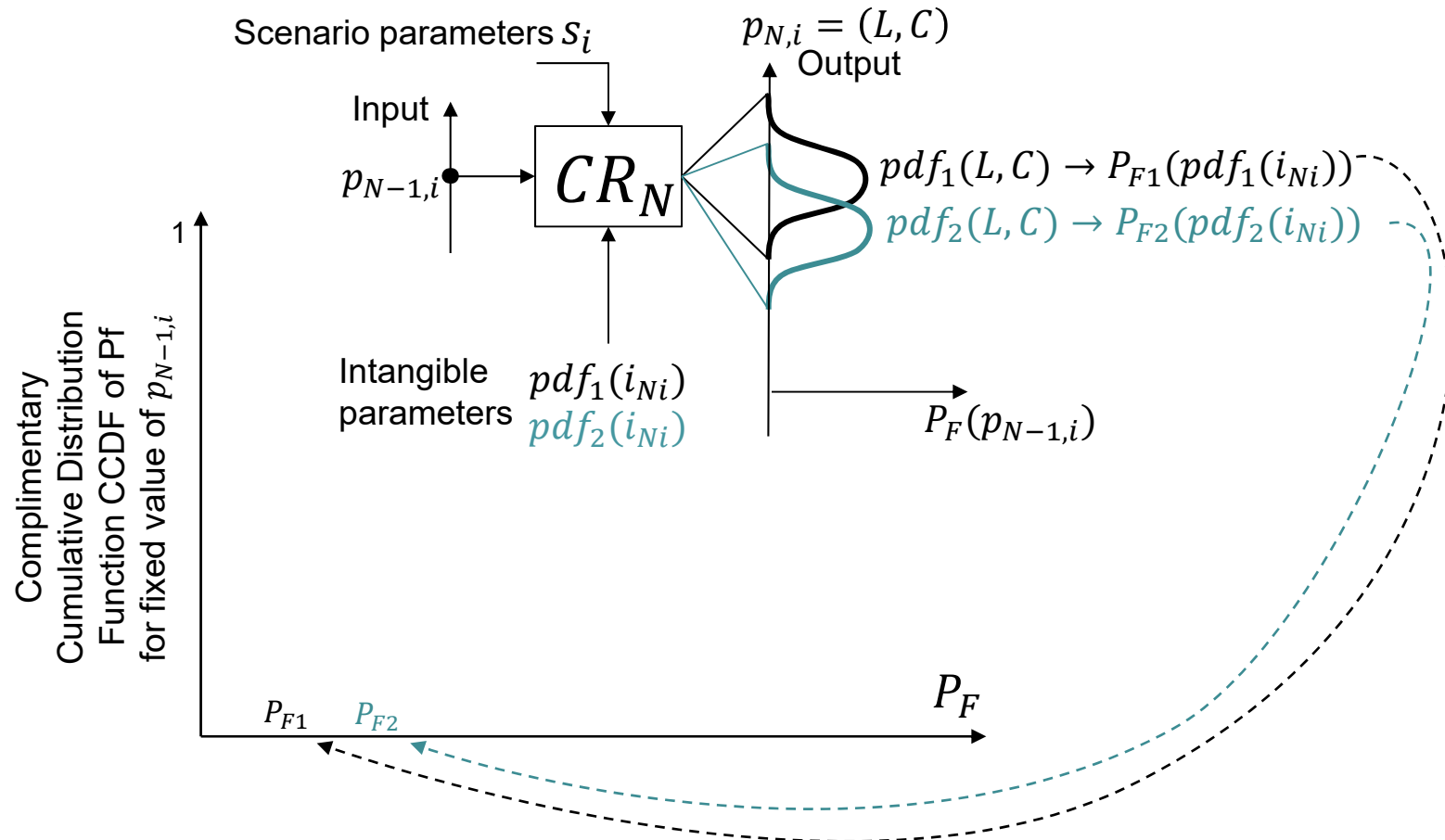
# Treatment of Model Intangible Parameters

- For given  $p_k$  different values of  $P_f$ , including the bounding ones, can be obtained by sampling in the space of the distributions.
- Result of the sampling is presented as a complementary cumulative distribution function  $CCDF(P_F)$



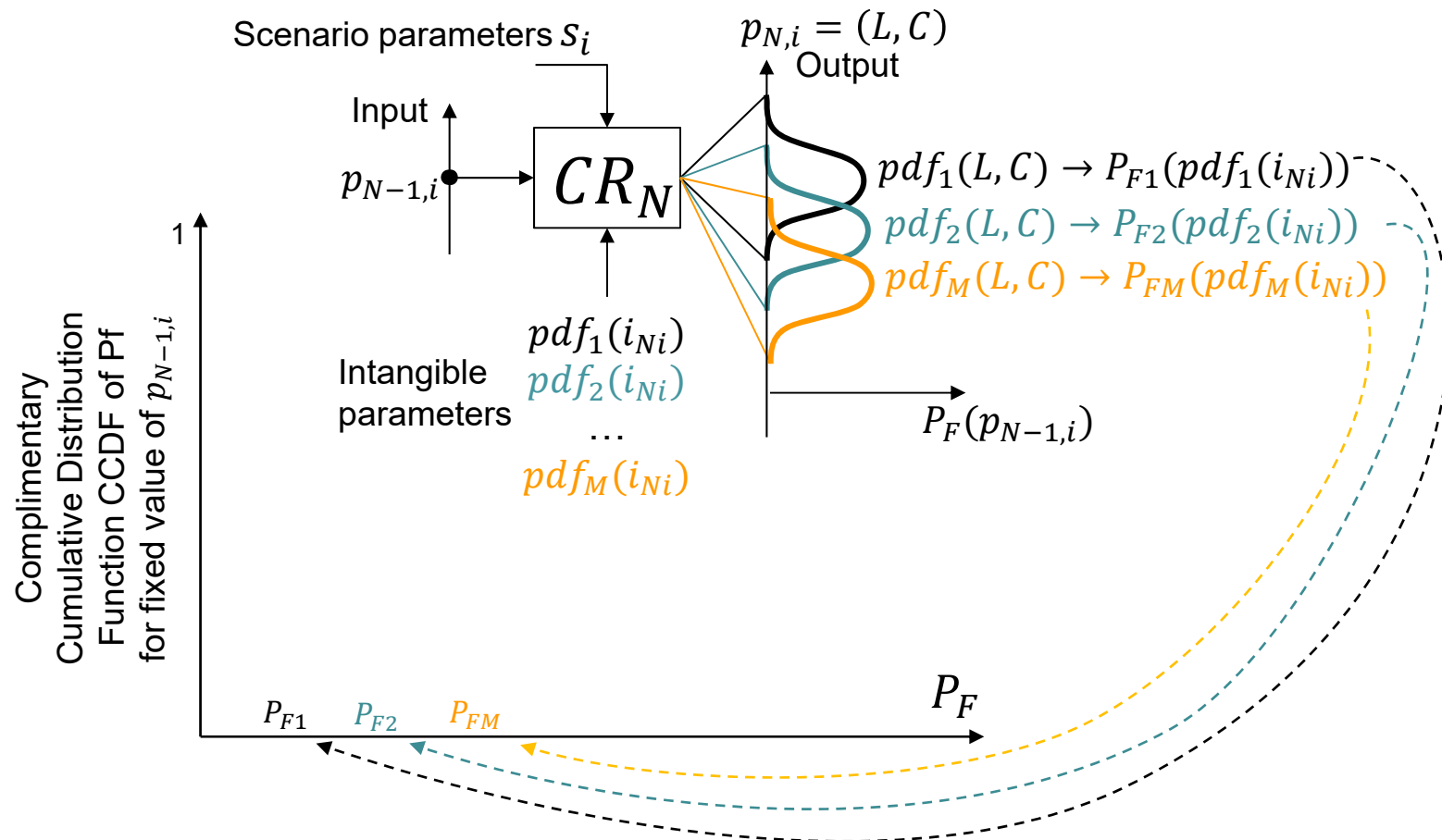
# Treatment of Model Intangible Parameters

- For given  $p_k$  different values of  $P_f$ , including the bounding ones, can be obtained by sampling in the space of the distributions.
- Result of the sampling is presented as a complementary cumulative distribution function  $CCDF(P_F)$



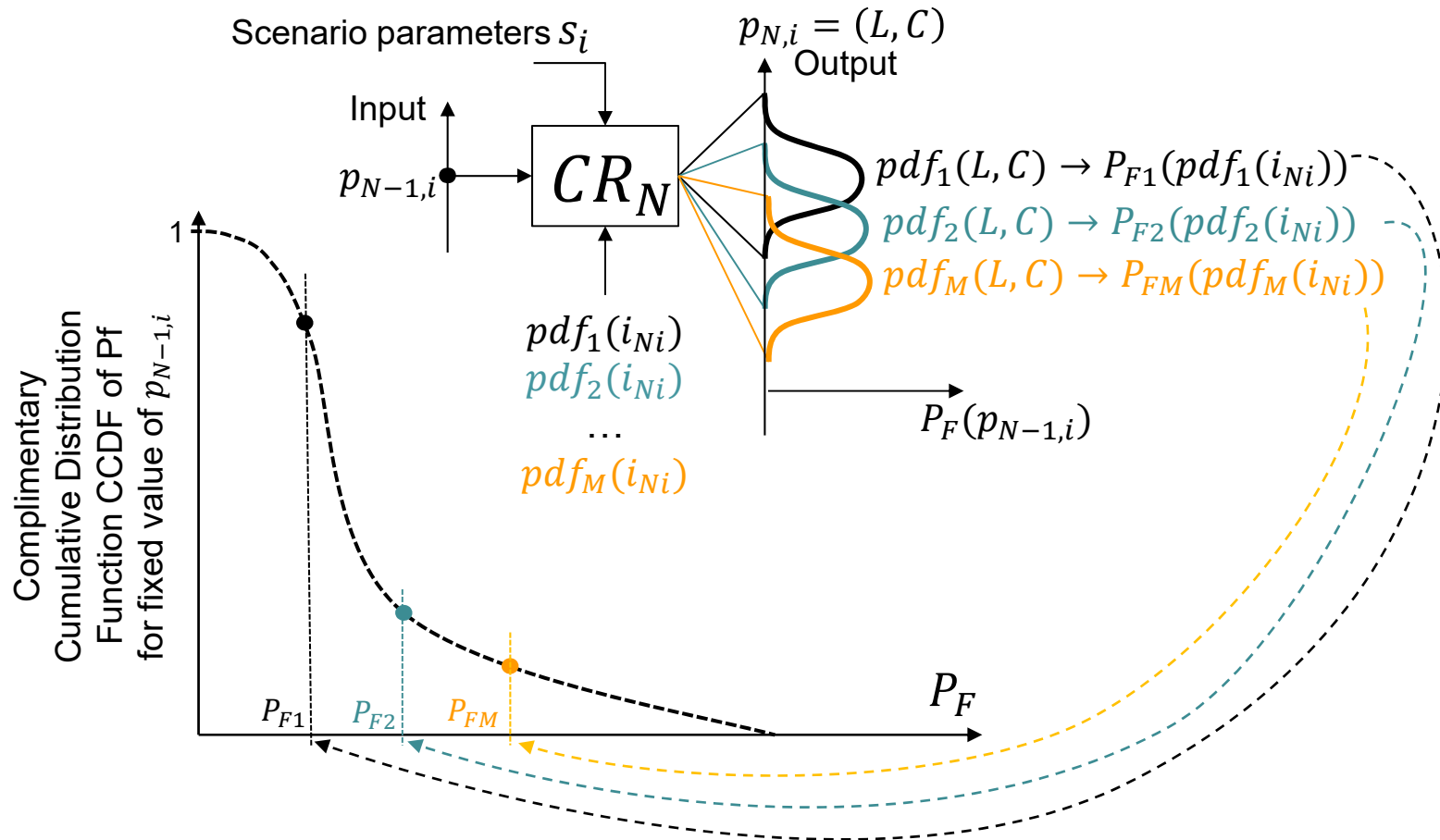
# Treatment of Model Intangible Parameters

- For given  $p_k$  different values of  $P_f$ , including the bounding ones, can be obtained by sampling in the space of the distributions.
- Result of the sampling is presented as a complementary cumulative distribution function  $CCDF(P_F)$



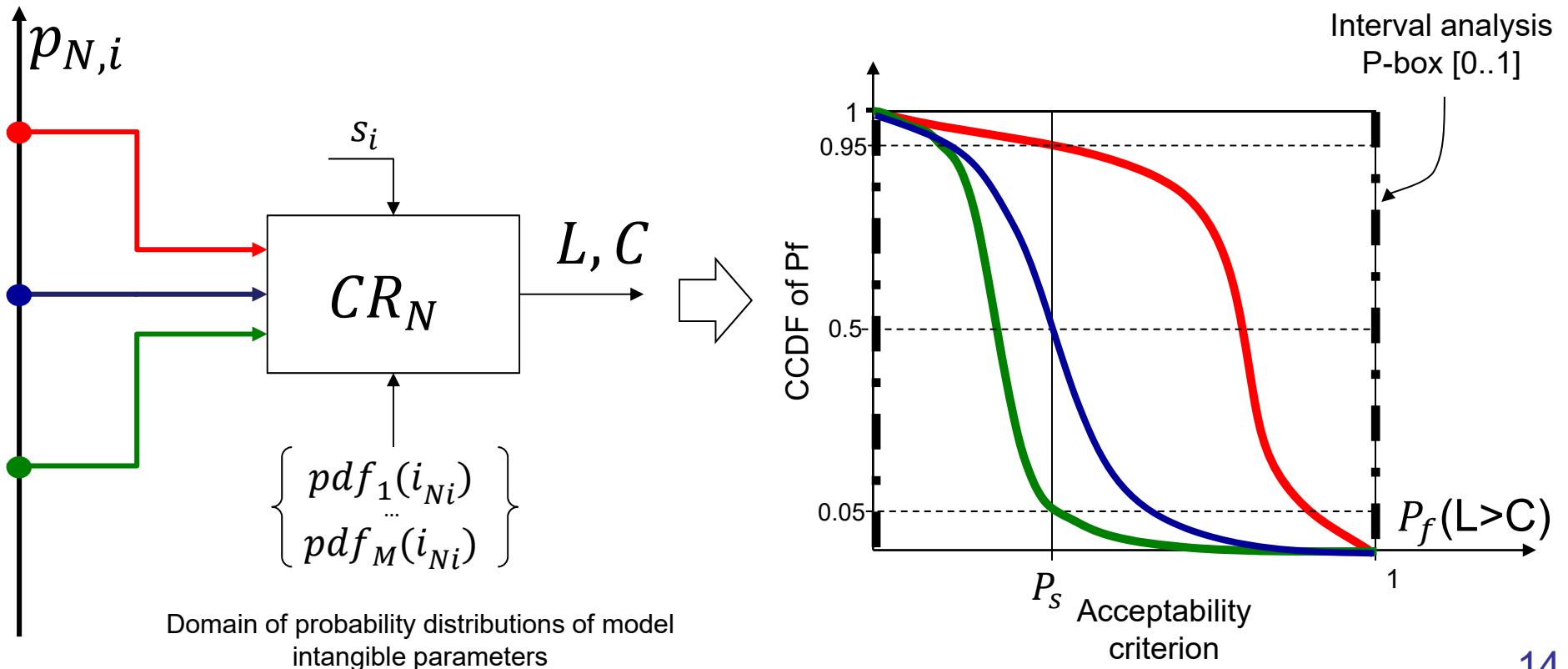
# Treatment of Model Intangible Parameters

- For given  $p_k$  different values of  $P_f$ , including the bounding ones, can be obtained by sampling in the space of the distributions.
- Result of the sampling is presented as a complementary cumulative distribution function  $CCDF(P_F)$



# How do we use CCDF of Pf?

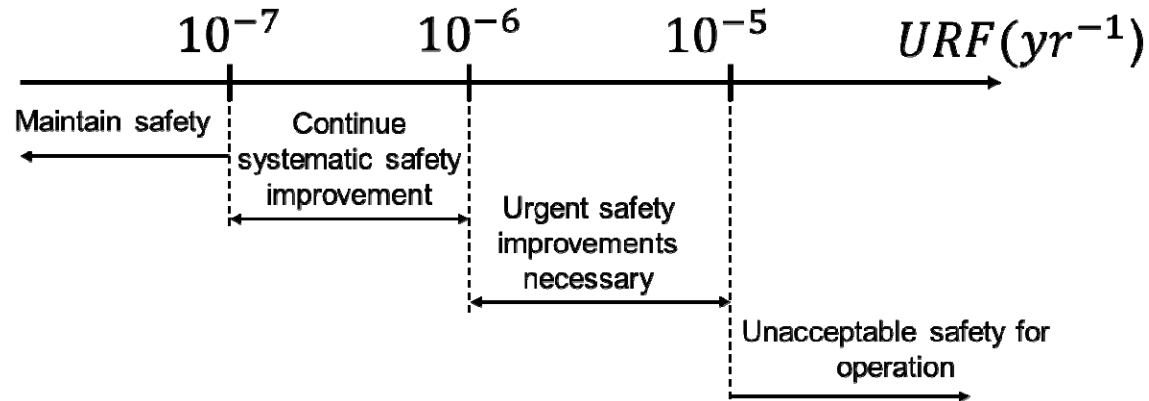
- From the interval analysis (P-box shown in the Figure), we can only say that  $P_f$  is between 0 and 1.
  - Such information is not very helpful for making conclusions on the risk acceptance.
- For every vector of the input parameters  $p_i$  we compute a CCDF of Pf.
  - For **green point** in  $p_i$ : 95% of the possible  $P_f$  values are below the screening probability  $P_s$ .
  - For **blue point** in  $p_i$ : 50% of the possible  $P_f$  values exceed screening probability  $P_s$ .
  - For **red point** in  $p_i$ : 95% of the possible  $P_f$  values exceed screening probability  $P_s$ .
    - The system is not safe with most (>95%) of the considered distributions of intangible parameters.
    - Improvement of knowledge about actual distribution of intangible parameters is not likely to change the decision.
- For “green” and “red” points It is possible to identify specific probability distributions of model intangible parameters that result in  $P_f$  **above** and **below** acceptability value, respectively.
  - Once identified, those distributions can be a subject to further research and quantification.



- Communication of ROAAM+ results

# Risk Acceptance and Decision Making

- Decisions are based on criteria for unacceptable release frequency  $URF (yr^{-1})$ .
  - Frequency is estimated by PSA tools.
  - Consequences (magnitude of the release) are estimated by deterministic severe accident codes such as MAAP.





# Risk Acceptance and Decision Making

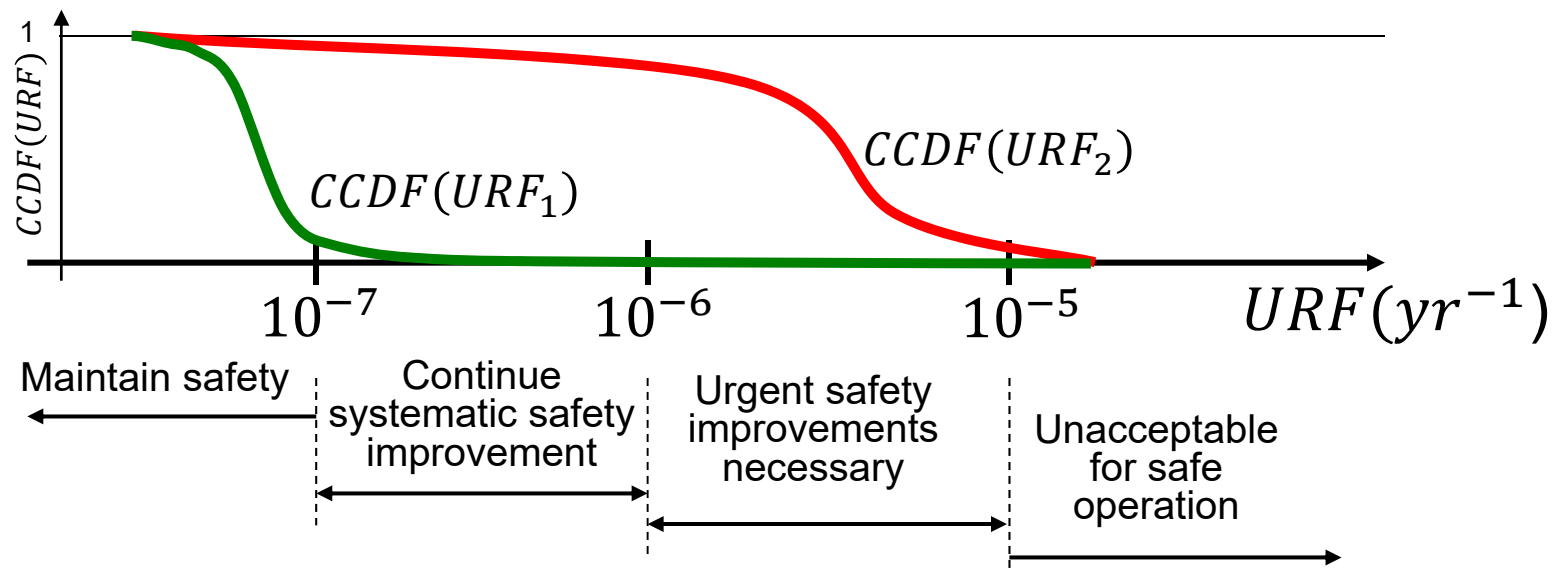
- Furthermore, the results of PSA L2 analysis can be evaluated according the relative safety significance by normalizing with respect to the goal value for unacceptable release frequency  $f_{Nominal}^U = 10^{-7} (year^{-1})$

- 
$$S^U = f^U / f_{Nominal}^U$$

Relative Safety Significance		Description
$S \geq 100$	Unacceptable	Unacceptable Safety for Operation - Risk-reducing measures must be taken immediately. If immediate risk reduction cannot be achieved the operation should be suspended until temporary or permanent risk mitigating measures have been taken.
$100 > S \geq 10$	Operation Limiting	Urgent safety improvements necessary – Temporary measures generally are necessary. Operation can continue for a limited period, depending on the medium term risk-increase. Cost-effective compensatory measures should be developed for permanent implementation.
$10 > S \geq 1$	Tolerable	Continue systematic safety improvement – Continue normal operation, no additional measures are necessary. Compensating measures should be considered and planned to the extent that this is considered reasonable.
$1 > S$	Negligible	Maintain safety – Continue normal operation, no additional measures are necessary.

# ROAAM+ and decision support

- Uncertainty in the assessment of the  $URF$  is recognized in the current decision making framework.
  - In case of inconclusive  $URF$  estimate
    - reduction of variance or conservatism may be justified.
- The uncertainty can be characterized as a  $CCDF(URF)$ .
- ROAAM+ is a decision oriented approach that provides
  - means for systematic and comprehensive quantification of uncertainty.
- The data on uncertainty can be directly utilized in PSA
  - Extending and making PSA representation of the uncertainty more adequate for the decision makers.



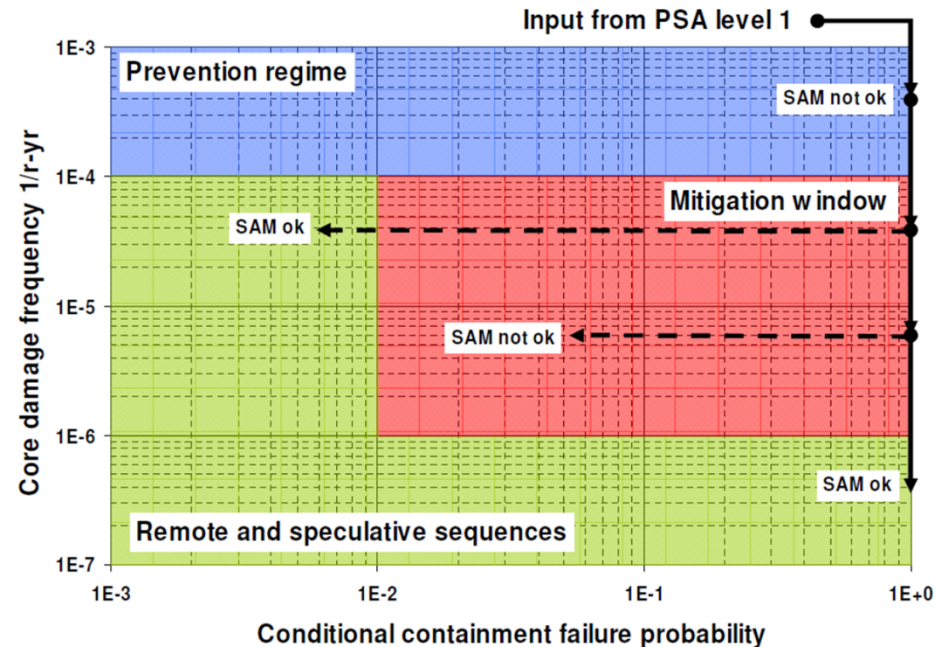
# ROAAM for Lovissa NPP: SAM mitigation window

- SAM mitigation window defines requirements for the reliability of the SAM measures for given scenarios of core damage with different frequencies.
- It can be used in order to assess decision criteria.

## Illustration for Integrated ROAAM

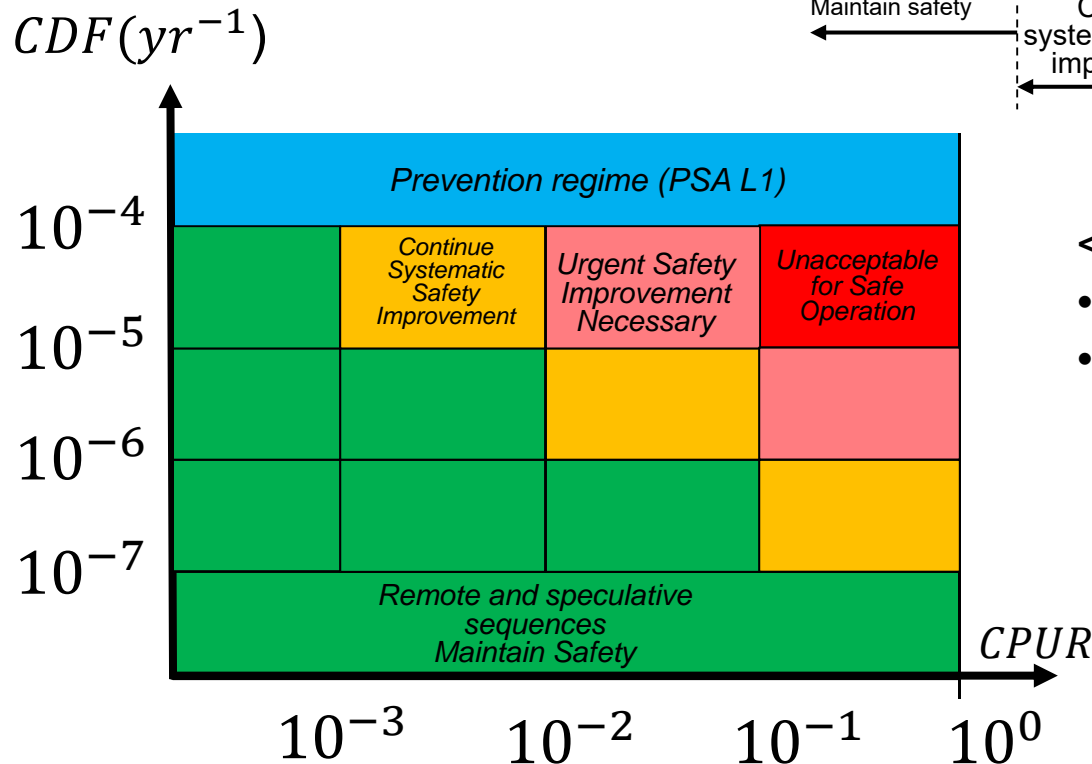
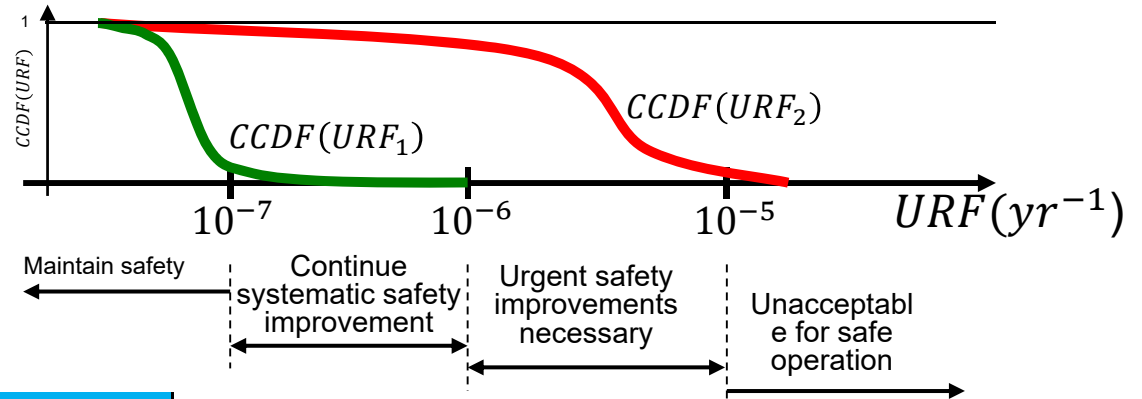
For Loviisa NPP

- screening frequency  $10^{-6}$  /r-yr
- design target for failure of each safeguards function  $< 10^{-2}$  / demand



# SAM mitigation window

- Information on frequencies of scenarios and probability of unacceptable release can be combined to assess the risk as a triplet  $R_i = \{s_i, f_i, P_i(c_i)\}$



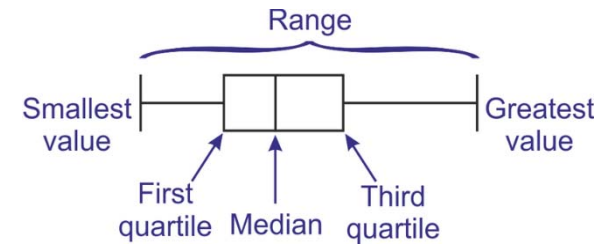
$\leq$  Integrated treatment

- Frequency for scenarios
- Conditional probability of unacceptable release ( $CPUR$ )
  - For the sake of conservatism at current stage  $CPUR$  can be considered equal to conditional containment failure probability  $CCFP$ .

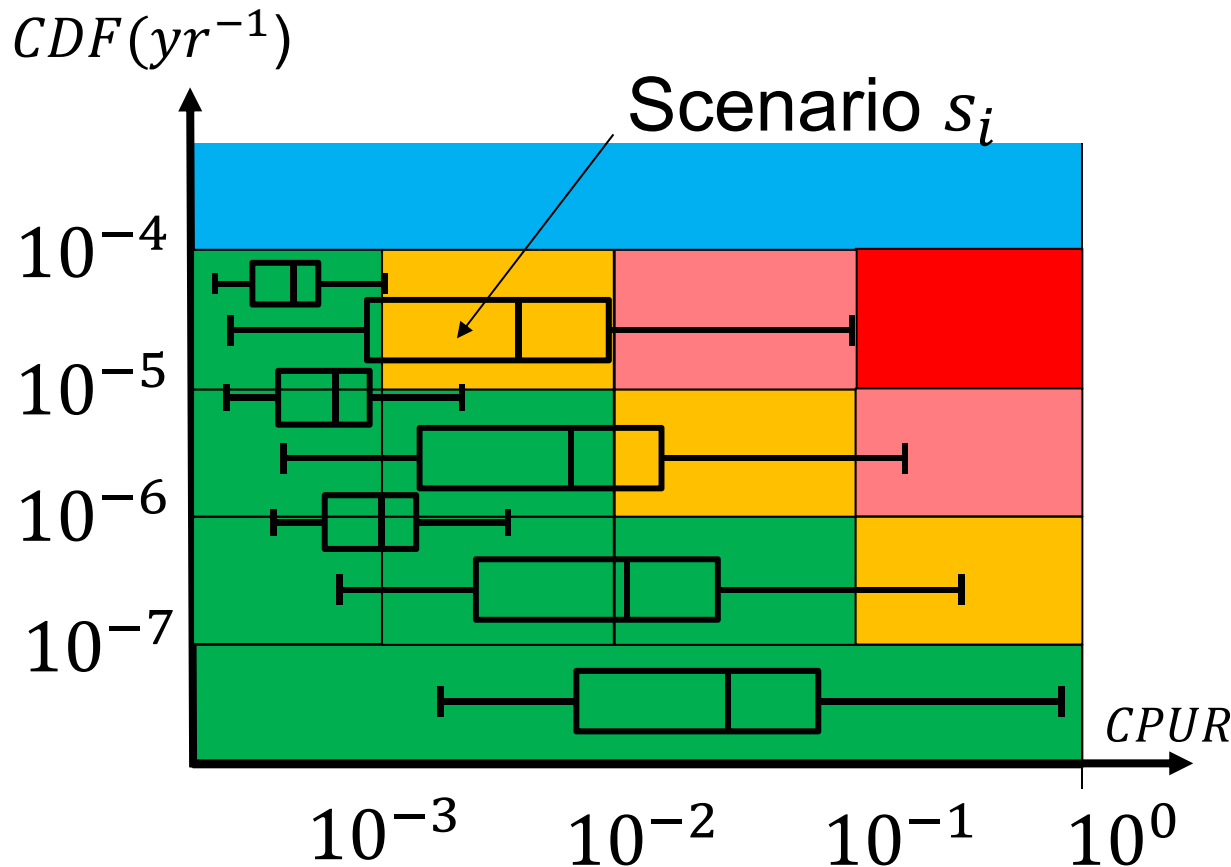
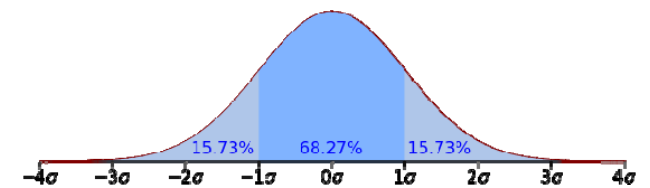
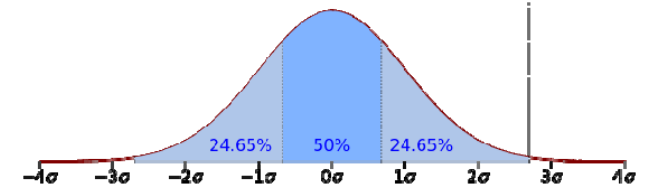
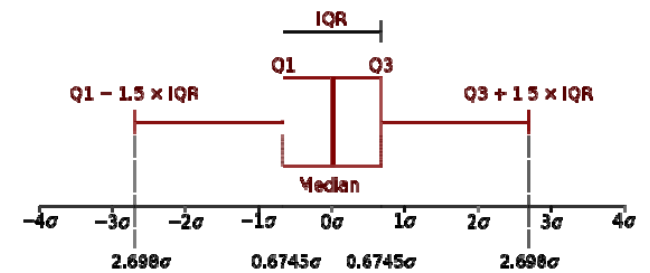
# SAM mitigation window and uncertainty in CCFP

- ROAAM+ can help to
  - Assess the uncertainty
  - Reduce the uncertainty
    - By improving knowledge and or modifying the design.

## box-and-whisker plot



or





## Example

---

- To illustrate the approach presented in this paper we consider a severe accident initiated by the station blackout (SBO) scenario.
  - In this work we consider plant damage state where the initiating event is a transient or a CCI, core cooling has failed and the reactor vessel pressure is low.
- We consider 2 following scenarios:
  - Unmitigated SBO – SBO1:
    - SBO with successful opening of SRV (314TA), ADS (314TB), systems 323 (LPCI/ECCS), 327 (HPCI/ECCS), 323 (Containment Sprays) considered unavailable. HS2-TL4 reference case
  - Recovered SBO – SBO2:
    - SBO with successful opening of SRV (314TA), ADS (314TB), LPCI/ECCS (323) can be restored after 7200sec, Systems 327 (HPCI/ECCS), 323 (Containment Sprays) considered unavailable. HS2-TL4 + Power recovery at 7200 sec.
    - In SBO2 we consider that the power (external grid or diesel generators) can be recovered after time delay (7200sec) and emergency core cooling system (ECCS) system can be restarted.



## Example (2)

---

- We use ROAAM+ framework:
  - To perform deterministic analysis of the accident progression:
    - From in-vessel accident progression vessel failure and melt release.
      - We use MELCOR code to perform analysis of in-vessel phase of accident progression, vessel failure and melt release and associated uncertainty.
    - To ex-vessel steam explosion.
      - Data from MELCOR code is used in SM for Ex-vessel steam explosion (SEIM) to predict corresponding loads on the containment due to ex-vessel steam explosion and associated uncertainty).
  - To quantify conditional containment failure probability due to ex-vessel steam explosion considering different fragility limits, i.e.  $6\text{kPa}\cdot\text{s}$  for containment hatch door that corresponds to original design and  $50\text{kPa}\cdot\text{s}$  for reinforced hatch door that represent possible design modification/improvement.

# Example (3)

- The results of ROAAM+ analysis are presented below:
  - note that there is a possibility to make deterministic analysis and models more realistic regarding some of the related parameters and models. The quantitative results should therefore be seen as indicative.

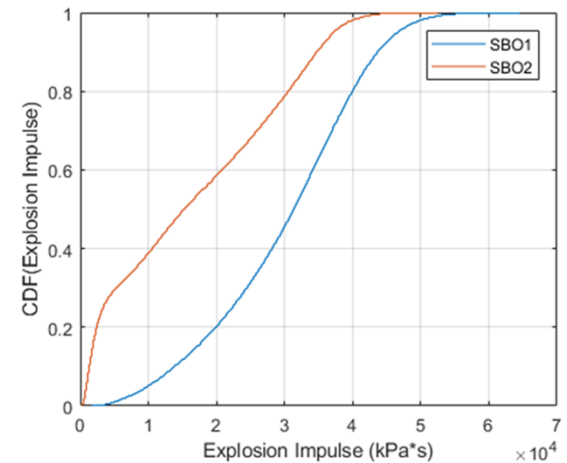
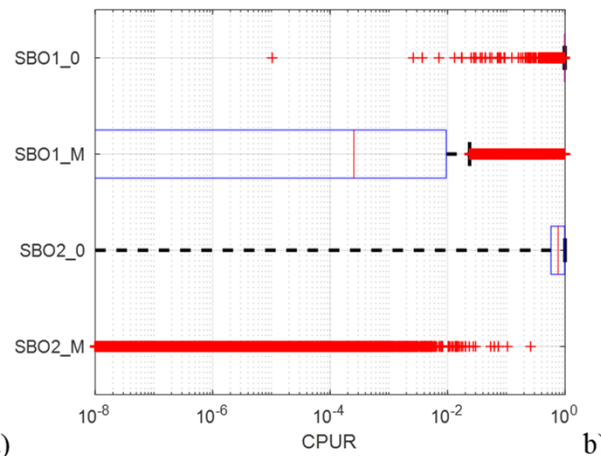
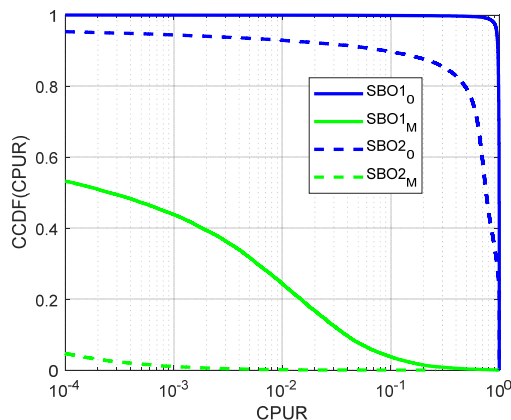


Figure. CCDF of Conditional Probability of Unacceptable Release a) due to ex-vessel steam explosion. (SBO1<sub>0</sub> – Unmitigated SBO with original design, SBO1<sub>M</sub> – unmitigated SBO with modified design, SBO2<sub>0</sub> – mitigated SBO with original design, SBO2<sub>M</sub> – mitigated SBO with modified design).

Figure. (a). Box and Whisker Plot<sup>1</sup> of Conditional Probability of Unacceptable Release due to ex-vessel steam explosion. (b). Distribution (CDF) of Ex-Vessel Steam Explosion Impulse (kPa\*s).





## Example (4)

---

- The expected values (expected value of CPUR) can be used directly in the assessment of compliance with the regulatory requirements.
- Alternatively, the distributions of conditional probability of unacceptable release, obtained with ROAAM+ framework, can be interpreted as exceedance probabilities for different domains (risk thresholds):
  - i.e. instead of using expected value (which is a measure of central tendency, therefore may not be desirable in ensuring the risk is below certain value) we can look into the probability of exceeding certain risk threshold (screening probability  $p_s$ ).

# Example (5)

- For example, let's consider the scenario frequency to be in the range of  $10^{-4}$  –  $10^{-5}$  and screening probabilities  $p_s = 1.e^{-3}$ ,  $1.e - 2$  and  $1.e-1$ , that corresponds to decision options: “maintain safety”, “continue systematic safety improvement”, “urgent safety improvements necessary”, “unacceptable safety for operation” or negligible, tolerable, operation limiting and unacceptable – safety significance.
- Then, in unmitigated SBO scenario (SBO1):
  - in the original design, the exceedance probability for “maintain safety”, “continue systematic safety improvement” and “urgent safety improvement is necessary” domains is 1, on the other hand for the modified design, exceedance probabilities are 0.438, 0.243 and 0.037, which corresponds to  $p_s = 1.e^{-3}$ ,  $1.e - 2$  and  $1.e-1$  correspondingly.
  - in mitigated scenario with water injection after 7200sec (SBO2), exceedance probabilities are 0.94, 0.92 and 0.89 for original design, and 0.01,  $1.3e-3$  and  $1.e-6$  for screening probability  $p_s = 1.e^{-3}$ ,  $1.e - 2$  and  $1.e-1$  correspondingly.

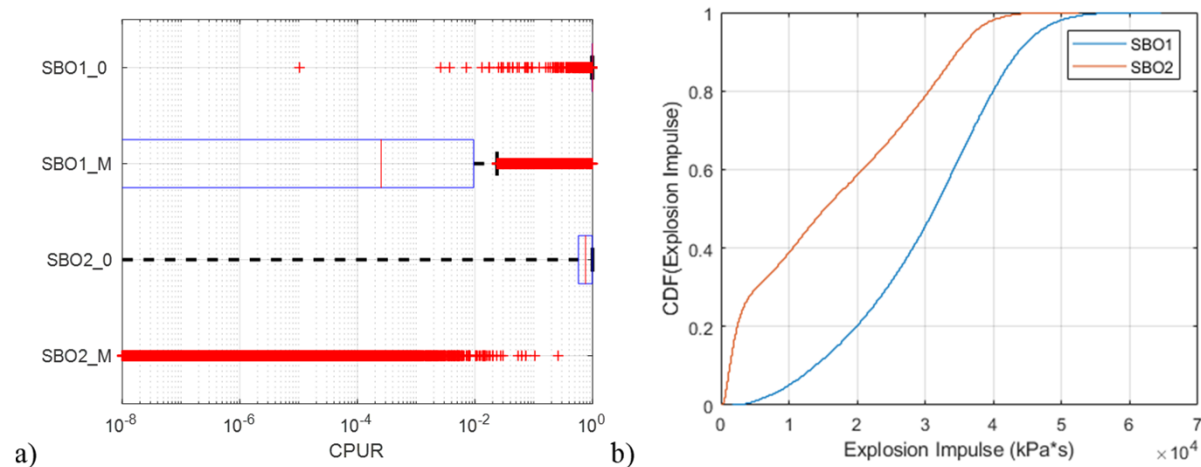


Figure. (a). Box and Whisker Plot<sup>1</sup> of Conditional Probability of Unacceptable Release due to ex-vessel steam explosion. (b). Distribution (CDF) of Ex-Vessel Steam Explosion Impulse (kPa\*s).

## Example (6)

- The results of ROAAM+ framework show the effect accident scenario and possible design modification on the CPUR. Design modification results in significant reduction of CPUR and existing SAM strategy can be considered as effective in modified design. However, depending on scenario ( $s_i$ ) frequency, since  $p_s = 1.e-3$  is only met for SBO2 scenario. In SBO1 scenario with modified design, below  $1.e-6$  for the sequence to be considered as remote and speculative.

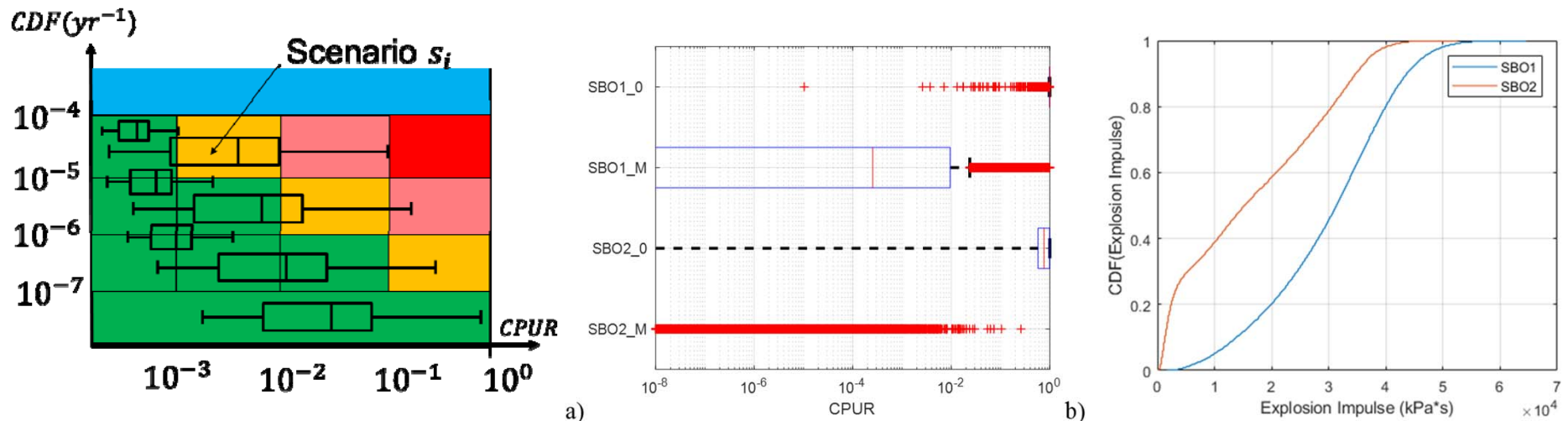


Figure. (a). Box and Whisker Plot<sup>1</sup> of Conditional Probability of Unacceptable Release due to ex-vessel steam explosion. (b). Distribution (CDF) of Ex-Vessel Steam Explosion Impulse ( $\text{kPa}\cdot\text{s}$ ).



## Example (7)

- Furthermore, obtained exceedance probability values can be used to calculate expected disutility (loss, cost) of different decision options (modify vs. maintain SAM) using equation:
  - $$U_C = U_0 * \text{cdf}(P_f < 1.e - 3) + U_R \text{cdf}(1.e - 3 < P_f < 1.e - 2) + U_{US} \text{cdf}(1.e - 2 < P_f < 1.e - 1) + U_{UO} \text{cdf}(1.e - 1 < P_f < 1)$$
- Where
  - $U_0$  – cost of “Maintain Safety”, which will be practically equal to zero.
  - $U_R$ -costs of “Continue Systematic Safety Improvement” (costs related to the research and further reduction of uncertainty)
  - $U_{US}$ -costs of “Urgent Safety Improvement” (costs related to urgent R&D, urgent design modification, and other economic losses related to NPP operation e.g. long shutdown;
  - $U_{UO}$ - costs of “Unacceptable for Safe Operation” – which include costs of reactor shutdown, long shutdown, etc.
- Additionally, it is possible to calculate design modification effectiveness measure with respect to potential consequences of containment failure and large early release (in terms of disutility).

## Example (8)

- These results can be used as an input to risk-informed decision making process:
  - Deterministic/Probabilistic Requirements.
  - Information for cost-benefit analysis.

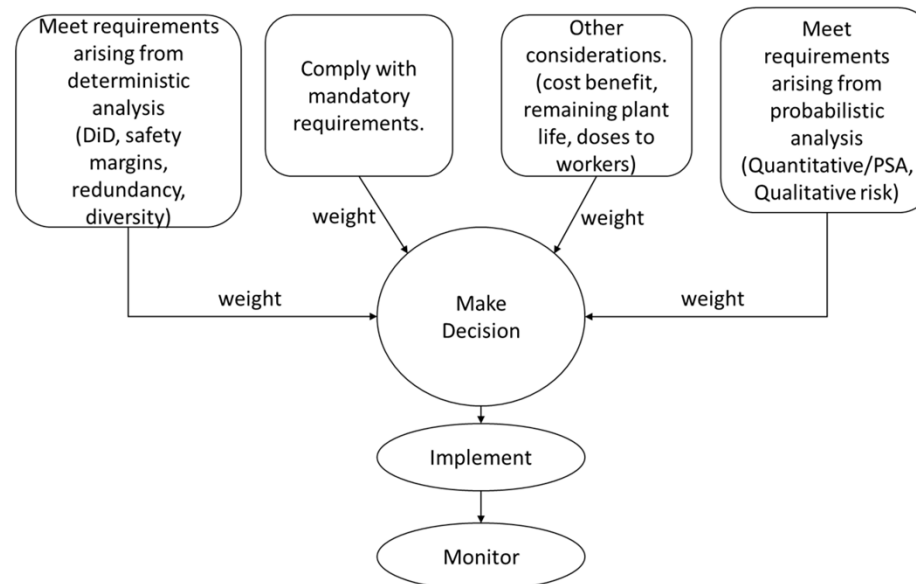


Figure. Risk-Informed Decision Making Process.



## Conclusions.

---

- The approach presented in this paper can be used for decision support and communication of ROAAM+ framework analysis results.
- ROAAM+ Framework results provide both deterministic and probabilistic insights, taking into account state-of-the-art knowledge, regarding the effectiveness of the SAM strategy, the effect possible design modifications on SAM and conditions where changes in the safety design can be justified.
  - Furthermore, ROAAM+ framework results can be used to improve the credibility and transparency of the level 2 PSA, by identifying the accident sequences where phenomena with risk significant consequences can occur and provide information regarding the probability (probability distributions) of failure due to these phenomena, which can additionally improve the credibility and transparency of the level 2 PSA.