The NARSIS project: objectives and main outcomes

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NARSIS
New Approach to Reactor Safety Improvements

Coordinator: CEA Commissariat à l'énergie atomique

Euratom Research and Training Programme: Research and Innovation action

In the presentation some materials are based on: NARSIS Project Handbook

List of participants

#	Participant Legal Name	Country
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6	INSTITUT DE RADIOPROTECTION ET DE SURETE NUCLEAIRE	France
7	AREVA GMBH	Germany
8	ELECTRICITE DE FRANCE	France
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11	Teknologian tutkimuskeskus VTT Oy	Finland
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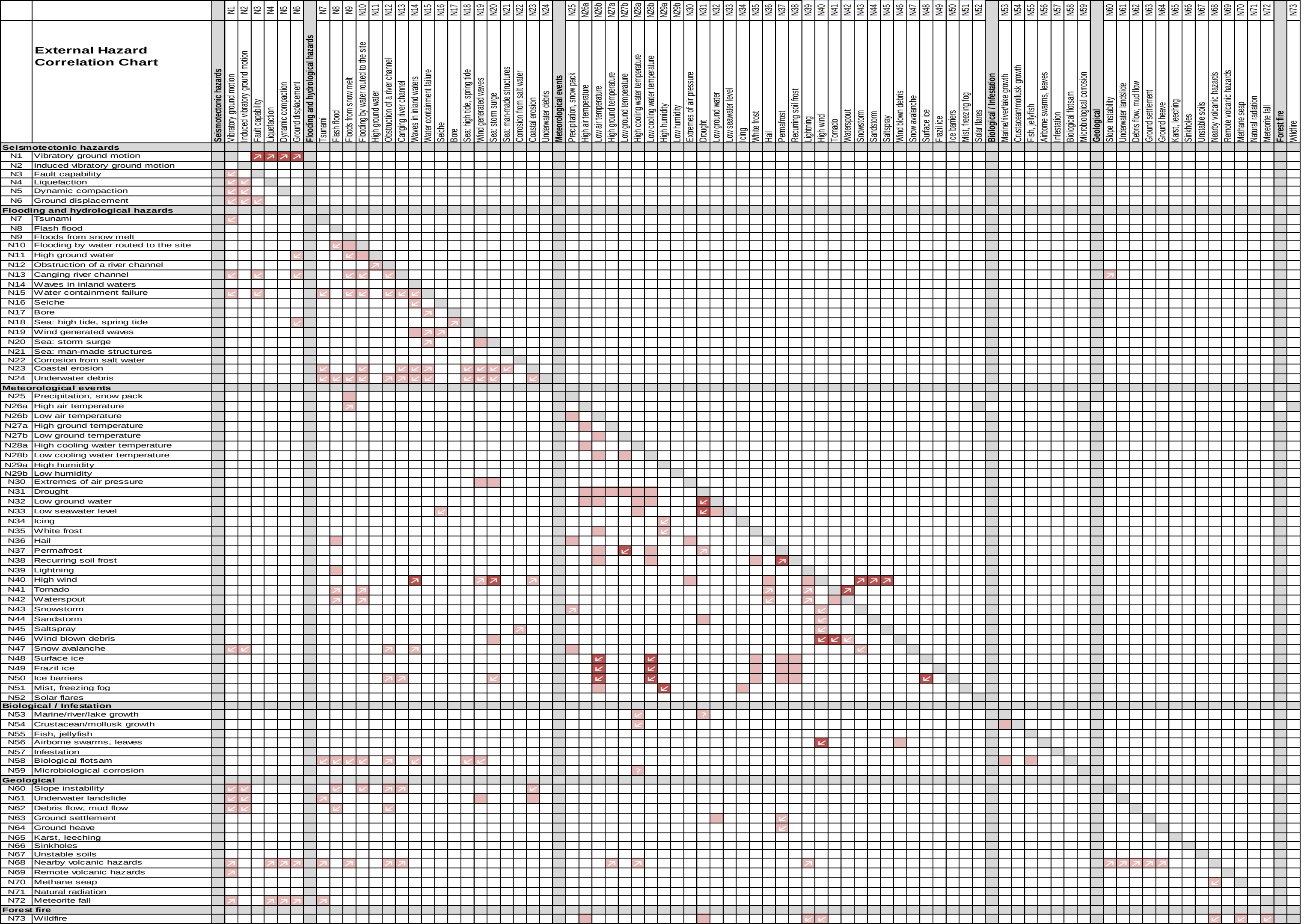
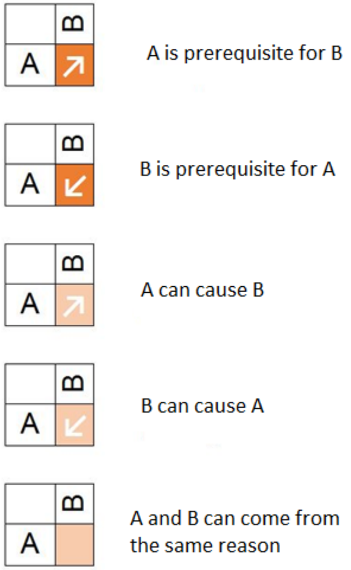
NARSIS objectives

- *Natural hazards characterization, considering concomitant external (simultaneous-yet-independent or cascading) events, and the correlation in intra-event intensity parameters;*
- *Fragility and functionality assessment of main critical NPPs' elements, accounting for conjunct effects (including ageing effects) and interdependencies under single or multiple external aggressions;*
- *Risk integration combined with uncertainty characterization and quantification, to allow efficient risks comparison and account for all possible interactions and cascade effects;*
- *Better processing/integration of expert-based information within PSA, through modern uncertainty theories both to represent in flexible manner experts' judgments and to aggregate them to be used in a comprehensive manner.*
- *The proposed improvements to be tested and validated on simplified and real NPP case studies. Demonstration supporting tools for operational & severe accident management will be also provided.*





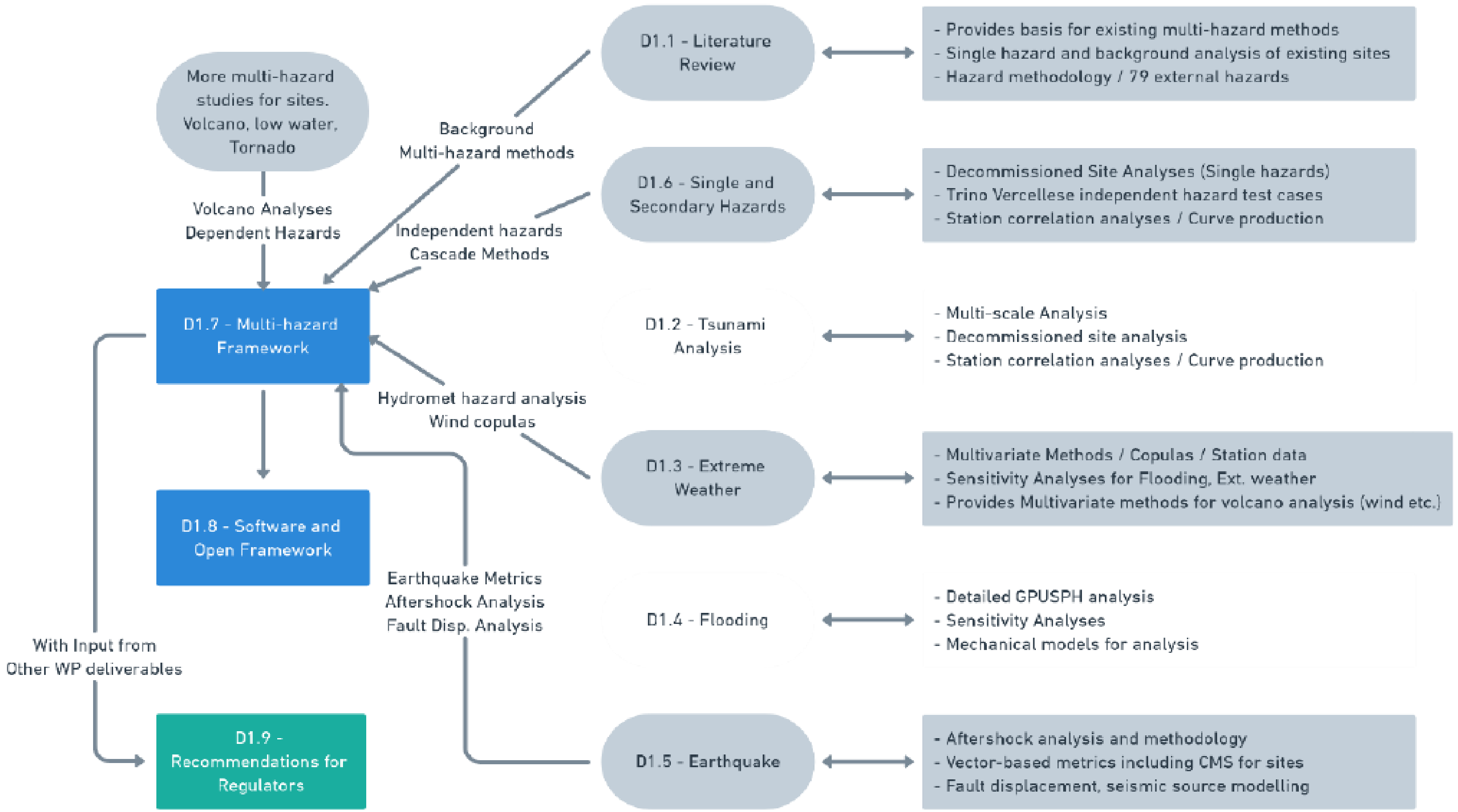
ASAMPSA_E: Correlation table for various external hazards

Multi-hazard framework (WP1)

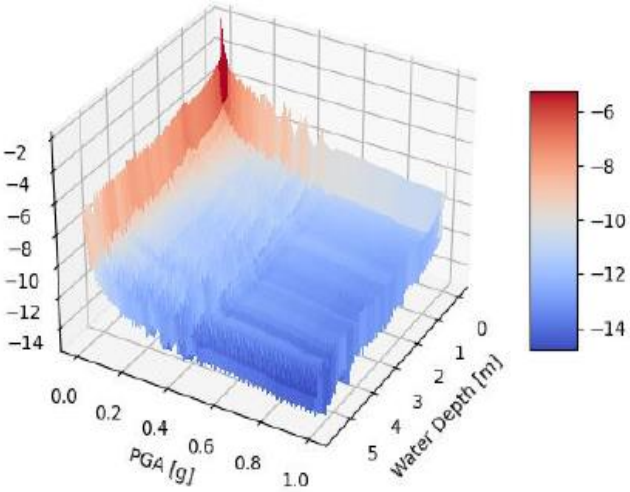
- New approaches for characterization of potential physical threats at nuclear installation exposed to different external natural hazards and scenarios, focusing on some of them identified as priorities by the PSA End-Users community in the ASAMPSA-E project: earthquakes, flooding, tsunamis and extreme weather.

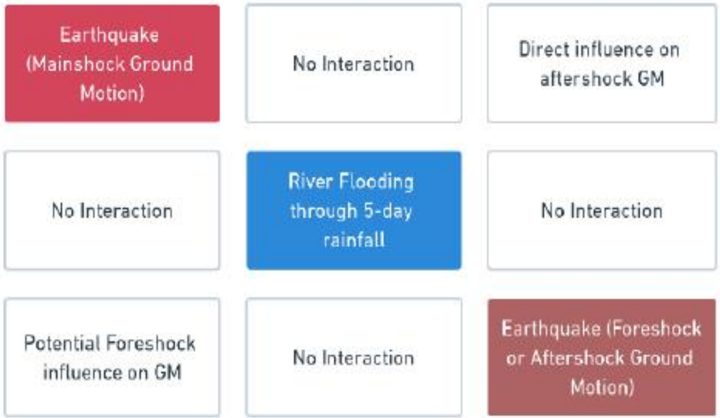
Proposed methodology:

- Level 0: Single hazard assessment through standard practice or improved methods
- Level 1: Multi-hazard assessment scoping through potential site-specific hazards
- Level 2: Multi-hazard interaction matrix and scoring
- Level 3: Modellability matrix
- Level 4: Quantitative analysis of multiple hazard probabilities


More multi-hazard studies for sites. Volcano, low water, Tornado
Volcano Analyses
Dependent Hazards
Background
Multi-hazard methods
Independent hazards
Cascade Methods
D1.7 - Multi-hazard Framework
Hydromet hazard analysis
Wind copulas
D1.8 - Software and Open Framework
Earthquake Metrics
Aftershock Analysis
Fault Disp. Analysis
With Input from
Other WP deliverables
D1.9 - Recommendations for Regulators
D1.1 - Literature Review
- Provides basis for existing multi-hazard methods
- Single hazard and background analysis of existing sites
- Hazard methodology / 79 external hazards
D1.6 - Single and Secondary Hazards
- Decommissioned Site Analyses (Single hazards)
- Trino Vercellese independent hazard test cases
- Station correlation analyses / Curve production
D1.2 - Tsunami Analysis
- Multi-scale Analysis
- Decommissioned site analysis
- Station correlation analyses / Curve production
D1.3 - Extreme Weather
- Multivariate Methods / Copulas / Station data
- Sensitivity Analyses for Flooding, Ext. weather
- Provides Multivariate methods for volcano analysis (wind etc.)
D1.4 - Flooding
- Detailed GPUSPH analysis
- Sensitivity Analyses
- Mechanical models for analysis
D1.5 - Earthquake
- Aftershock analysis and methodology
- Vector-based metrics including CMS for sites
- Fault displacement, seismic source modelling

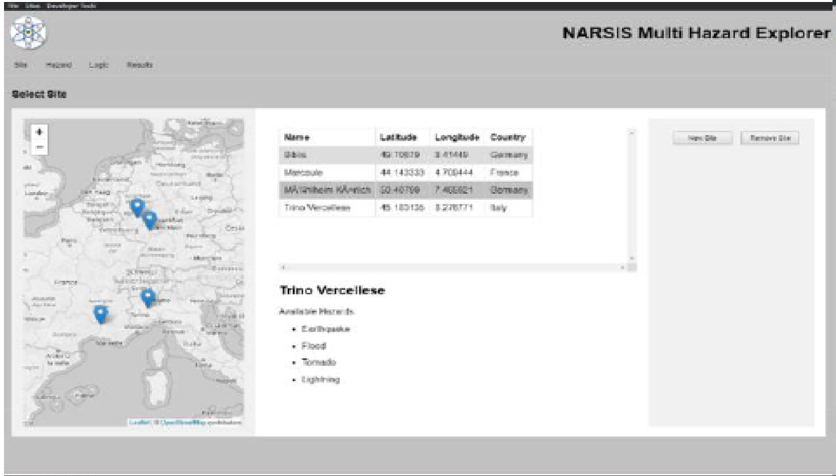
Examples: earthquake-flood

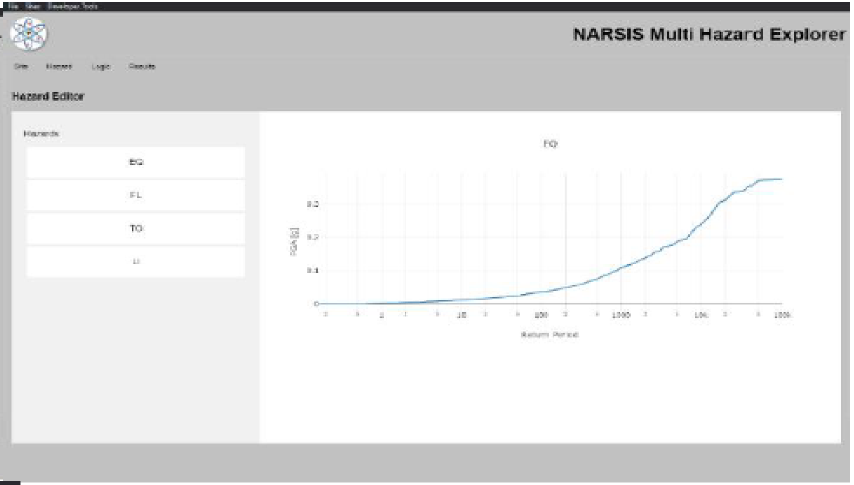


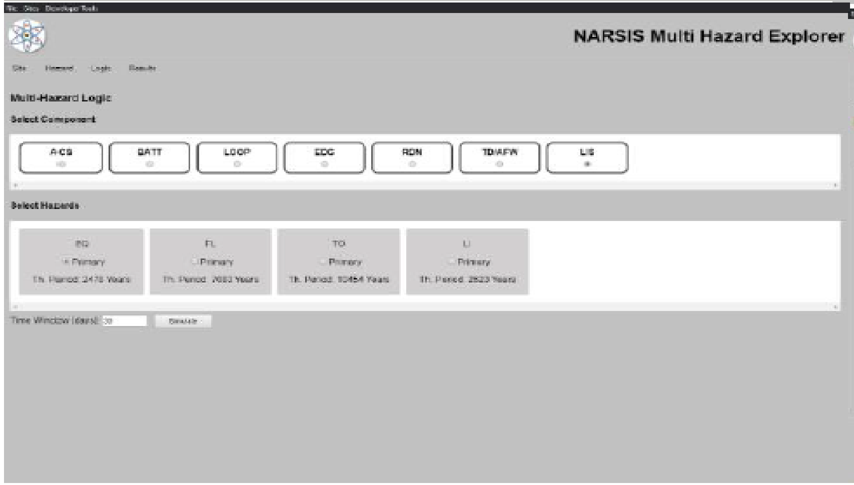


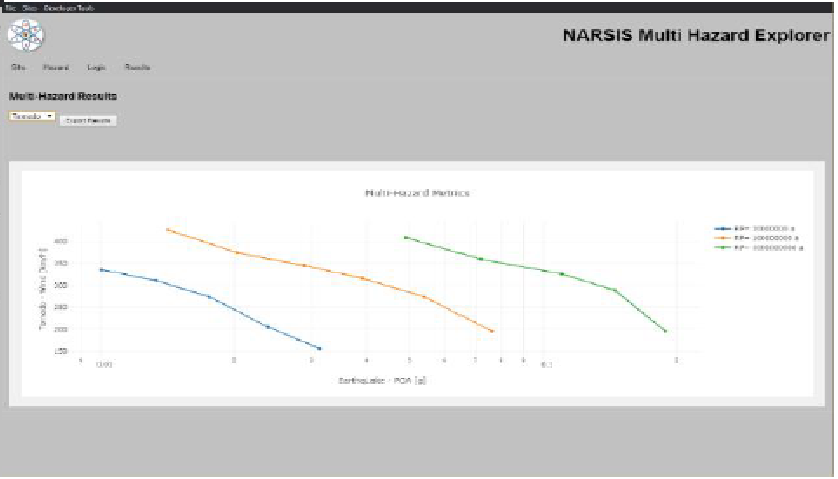
Earthquake-Flood interactions:
(left) probability curves for different durations (1 day, look-ahead time).
Colour bar indicates the log10 annual probability;
(right) the multi-hazard approach

NARSIS Multi-Hazard Explorer (MHE)









Recommendation for regulators

- The approach developed makes the multi-hazard assessment possible at the scale of a power plant. Calibration for analysed NPP is needed.
- The Level 0 (assessment of single hazards) is essential as it drives the quality and accuracy of the rest of the methodology.
- The hazard characterisation methods are very different, using deterministic or probabilistic methods, with regards to the hazard type. The current methods applied for four natural hazards: earthquake, tsunami, flooding and extreme weather.
- Possible impact of non-stationarity of some extreme events (for example weather hazards due to climate change).
- The step from single to multi-hazard analysis involves the identification of secondary hazards and the consideration of spatial or temporal interactions. The integrated framework enables to check all the possible combinations of single hazards, to qualify different types of interactions and to assess quantitatively (via the hazard interaction index), the credibility and intensity of these interactions.
- Uncertainty forms a major part of any result, given the large variability of events.

Fragility analysis (WP2)

- Developing innovative methods to increase the reliability or reduce the uncertainties in the estimation of the responses of main NPP critical elements to external threats.

Step 1: Identifying critical components of NPP

- The PSA importance measure criteria used to identify candidate safety significant SSC’s are:
  - Sum of FV (Fussell-Vesely index) for all basic events modeling the SSC of interest, including common cause failure (CCF) > 0.005
  - Maximum of component basic event RAW (Risk Achievement Worth) > 2
  - Maximum of applicable common cause basic events RAW > 20.
- Fussell-Vesely Importance Measure is the probability, given that a critical failure has occurred, that at least one minimal cut set containing a particular element contributed to that failure.
- Risk Achievement Worth (RAW) is the increase in risk if the feature is assumed to be failed at all times

Fragility analysis (WP2)

Critical elements for Level 1 PSA:

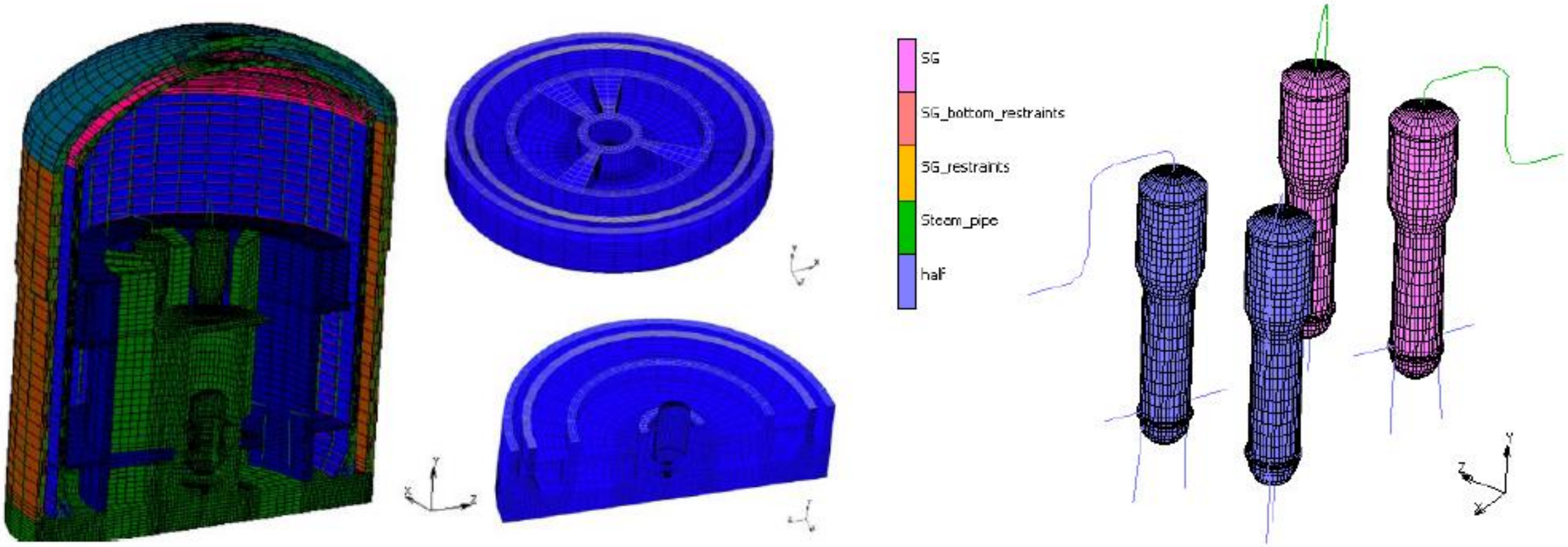
- I&C and switchgear cabinets/devices;
- Fuel assembly spacer grids and, more generally, reactor pressure vessel internals: the relevance of these elements is also confirmed by other case studies besides the one used for the importance ranking in the project;
- Distributed systems (HVAC, piping, cable raceways).

For Level 2 PSA, the following safety functions are identified as critical in decreasing order:

- primary circuit depressurization systems,
- active isolation of the reactor containment building,
- passive reactor building resistance and leaktightness in severe accident conditions (pressure and temperature),
- depressurization of the reactor building (by a filtered containment venting system),
- annulus venting system for NPP with double wall containment, auxiliary buildings filtration and venting,
- hydrogen risk management provisions.

Fragility analysis (WP2)

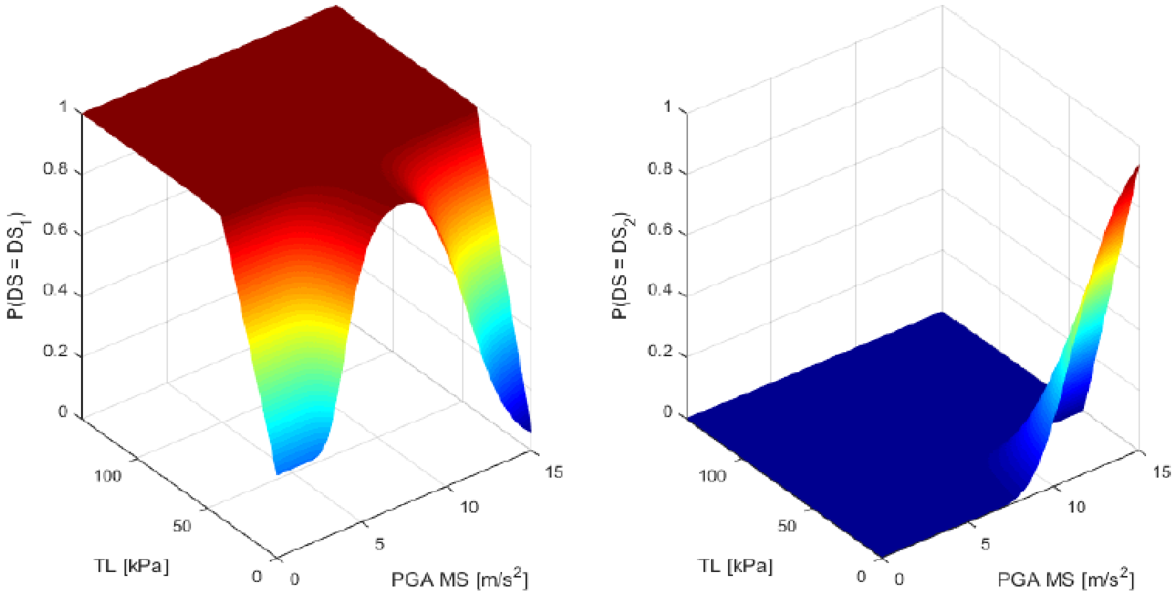
Step 2: Accounting for cumulative effects in fragility assessment



FE model of the containment system and steam generators with pipe

Fragility analysis (WP2)

Step 3: Deriving vector-valued fragility functions



Probability of the levee being in state DS1 (Left) and DS2 (Right) with respect to mainshock PGA (PGA MS) and tephra load (TL).

Main findings

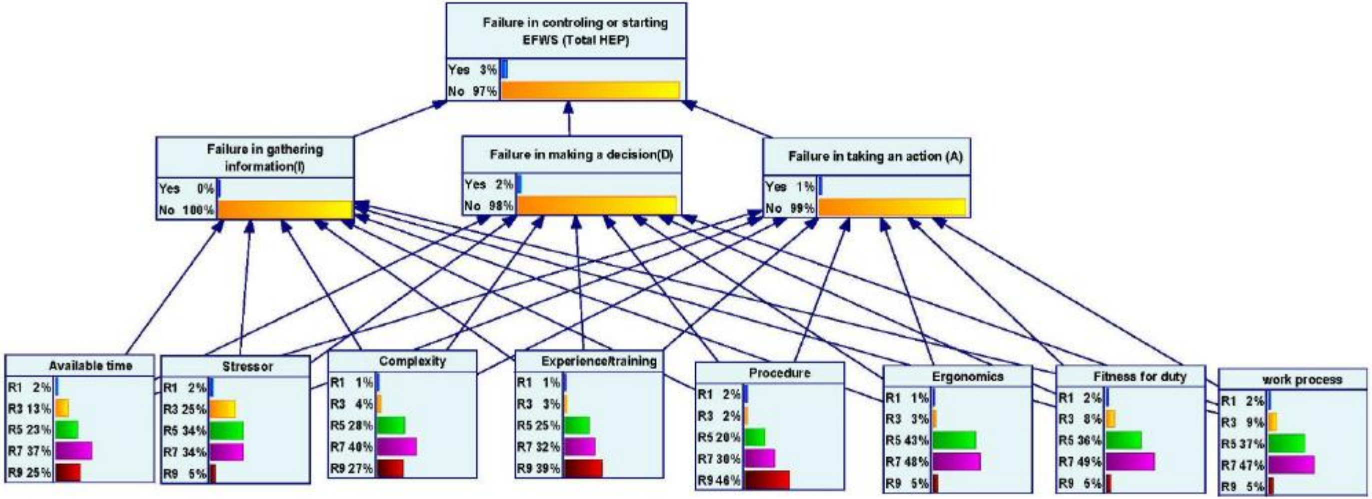
- Carefully selected vector-IMs make excellent candidates in terms of IM sufficiency and efficiency, when compared to scalar IMs.
- Vector-valued fragility functions tend to generate less dispersion (i.e. aleatory uncertainty due to record-to-record variability) than scalar-IM fragility curves: this difference may be interpreted as a partial transfer from the record-to-record variability to an epistemic uncertainty component that is related to the description of the seismic loading given the hazard at the studied site.
- The conditional spectrum method for the selection of input ground-motion records appears to be compatible with the derivation of vector-based fragility functions, since the hazard consistency is maintained throughout the scaling levels: such a framework is especially well adapted when considering spectral accelerations at various periods as vector-IMs.

The Multi-risk integration framework for safety analysis (WP3)

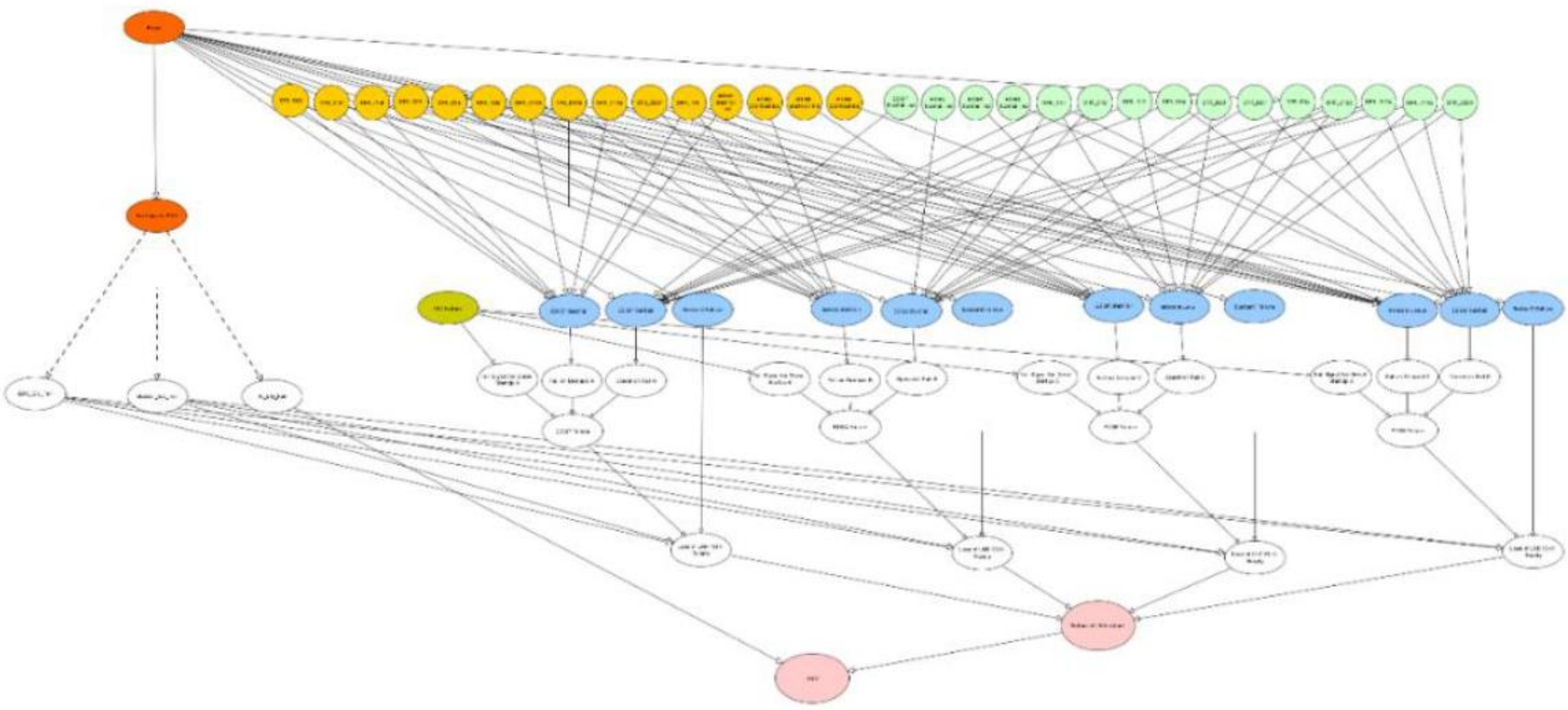
Improving the integration of external hazards and their consequences with existing state-of-the-art risk assessment

Identifying the most influential sources of uncertainty and to prioritise those which should be reduced accordingly

Proposed methodology: Bayesian Network including human and organisational aspects



The Multi-risk integration framework for safety analysis (WP3)



Main findings

- The advantages and challenges associated with the use of BNs, as compared to fault trees, were demonstrated using the chosen NPP accident scenario.
- The new approach to CCF modelling using BNs, based on correlation between component failures, was shown to have advantages over conventional parametric models.
- Within a multi-hazard risk problem, vector-based fragility of components was modelled within BNs. This allows for the inclusion of more than one intensity measure for each hazard, within a multi-hazard risk BN.
- The BN was also used as a surrogate model for advanced numerical methods used in reliability assessment of flood control dikes. Such surrogate BNs, modelling the reliability of components/sub-systems, can ease computational demands and as well, provide a direct link to a larger BN, estimating overall system risk.
- The new BN-SLIM, developed for the estimation of human error probability, was shown to compare favourably with existing methods.
- A step-wise, iterative framework for multi-hazard risk integration, using BNs, was presented. Using this framework, the technical and human BNs, with their respective developments and features, were integrated under a single BN-based risk model.

Constraining uncertainties

- Constraining uncertainty in BN modeling: typical approach is based on sensitivity functions for discrete BNs and on partial derivatives for continuous BNs while new approach is based on Boosted Beta Regression
- Constraining uncertainty in fragility assessment: combining Artificial Neural Network, adaptive training algorithm and amplification-factor-based construction of the likelihood function
- Constraining uncertainty in expert-based information

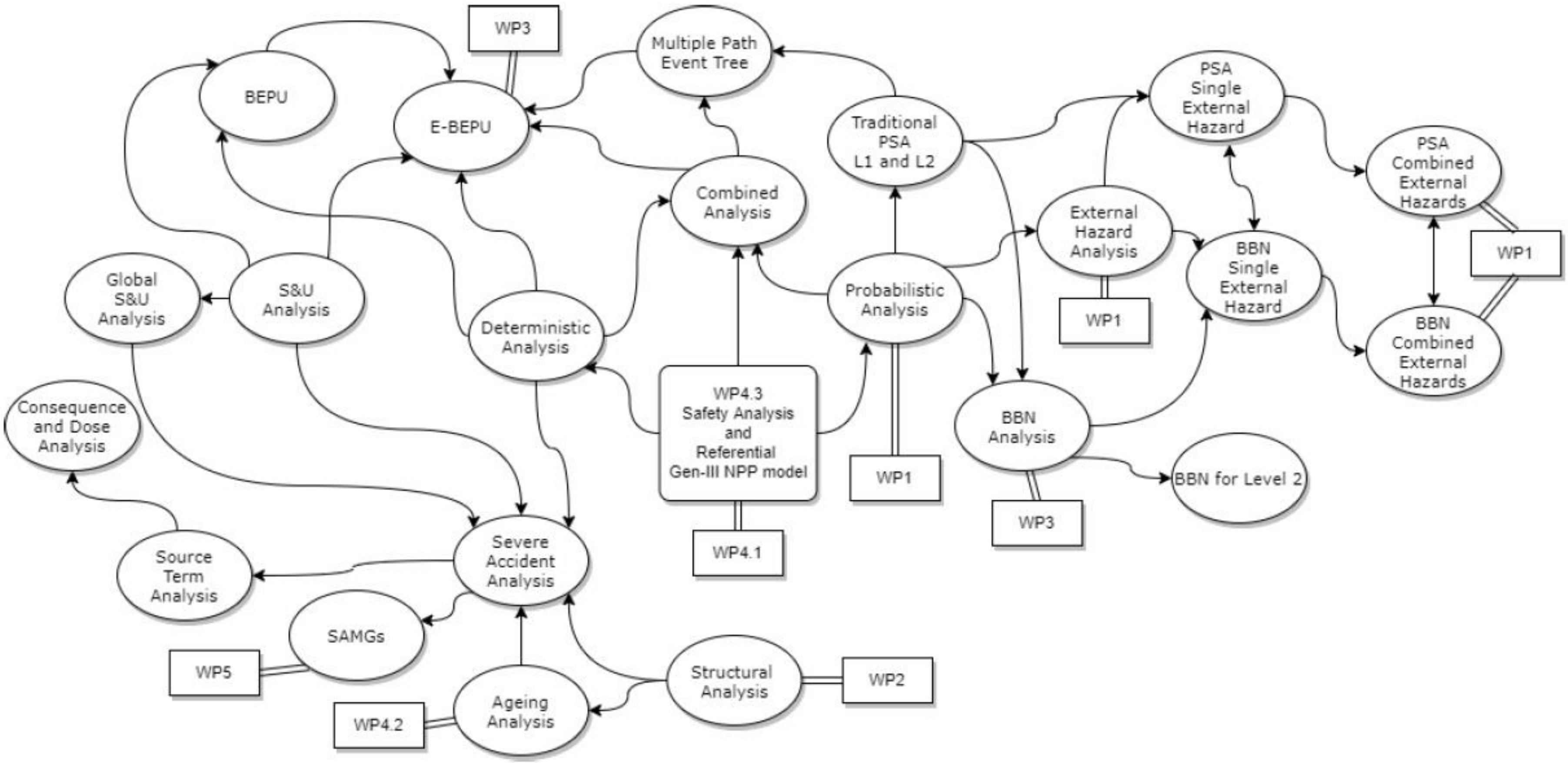
Applying and comparing various approaches for safety assessment (WP4)

- Development and application of model reduction strategies for assessing the impact of external hazards on the fragility of critical systems/components from a probabilistic viewpoint.
- Applying and comparing new and existing methods for deterministic, probabilistic and combined probabilistic-deterministic safety analyses, for referential Generation-III NPP.

Applying and comparing various approaches for safety assessment (WP4)

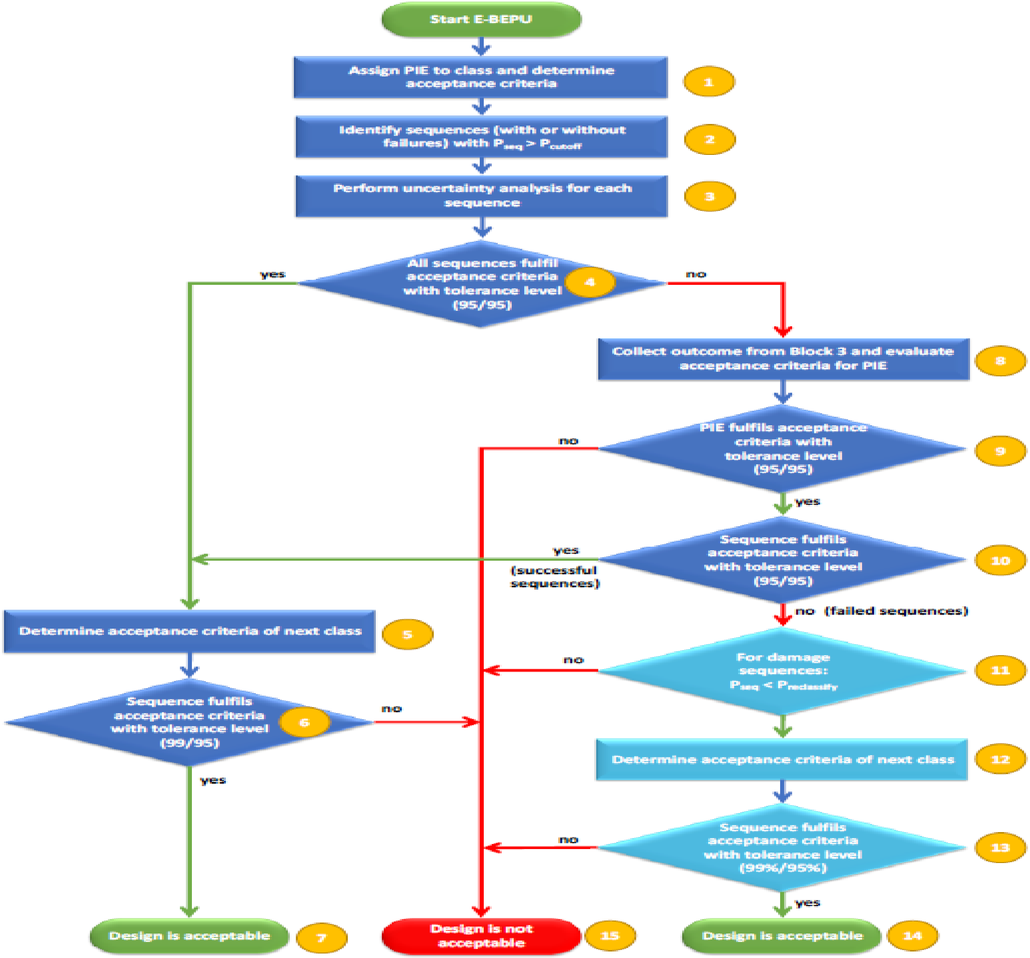
- New and existing methods for deterministic analysis in case of severe accident;
- Fully probabilistic analysis (BBN), with BBN application and comparison with a more traditional PSA approach based on Fault Trees (FT) and Event Trees (ET) in case of single and multiple hazard scenarios;
- Combined probabilistic-deterministic analysis (E-BEPU), which was applied for the first time in safety analysis.

Applying and comparing various approaches (WP4)

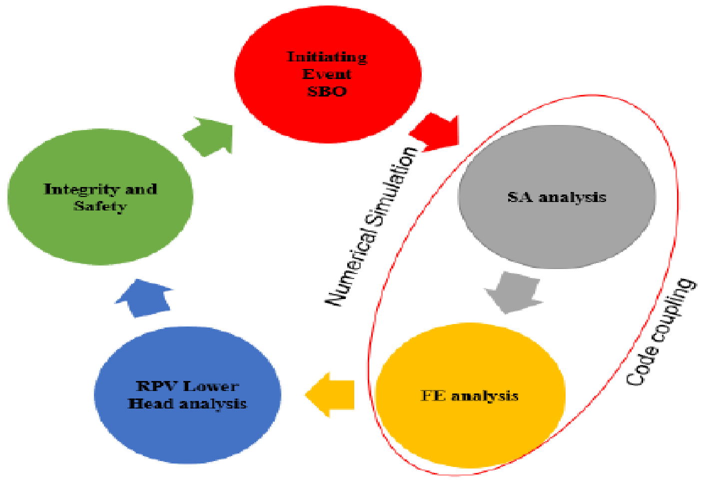


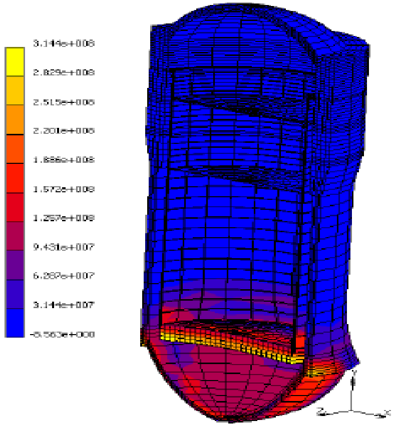
E-BEPU: Extended Best Estimate Plus Uncertainty

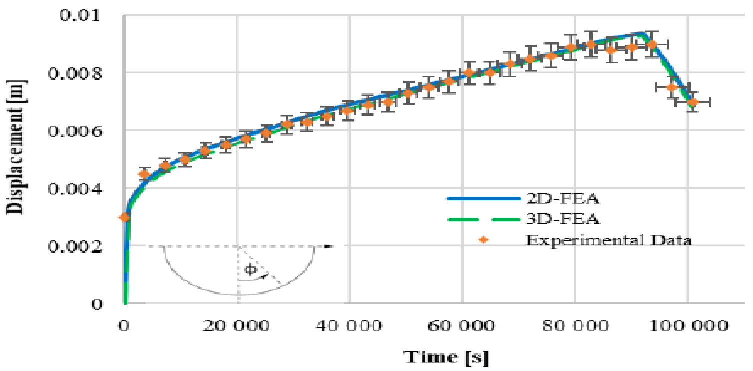
E-BEPU allows for the introduction of new criteria oriented to address better other aspects of the plant safety, such as defense-in-depth or robustness of the safety design (mainly avoidance of cliff-edges)



Ageing effects modelling based on FE







Main findings

- Multi-hazard modeling in traditional PSA is not straightforward.
- The adopted approach is strongly dependent on the PSA tools applied.
- Additional information on SSC behavior is needed when external events are considered.
- An increase of external hazards would harshly increase the complexity of the modeling.

Comparison of BN and traditional PSA

- For each FT, there is an equivalent BN. The inverse is not always true.
- BNs provide an added advantage in fault diagnostics in that new evidence can be easily incorporated into the model as Bayesian updating is inherent to BNs.
- Diagnostic inference in the BN enables a more direct evaluation of individual component contribution to system failure than the cutset approach adopted in fault tree analyses.
- Unforeseen dependencies may be identified during fault diagnosis in BNs as compared to fault tree analysis, where cutsets follow predetermined paths to failure and provide no information about the occurrence or non-occurrence of basic events that are not included in these cutsets.

Comparison of BN and traditional PSA

- Multi-state variables can more directly be incorporated into BNs. The number of entries in conditional probability tables increases exponentially with the number of states, making BN construction and computation hard.
- BNs inherently consider statistical dependencies between variables. Hence, the consideration of CCFs is easily included.
- BNs can directly incorporate continuous random variables without the need for additional modifications, as in the case of fault trees.
- In BNs, logical interactions between events and components are not visually represented as in fault trees, hidden within conditional probability.
- For complex systems with increased common cause effects, BNs can grow in size, making visualization and computations challenging. This is a significant downside of BNs, as dependencies between components become visually indecipherable.

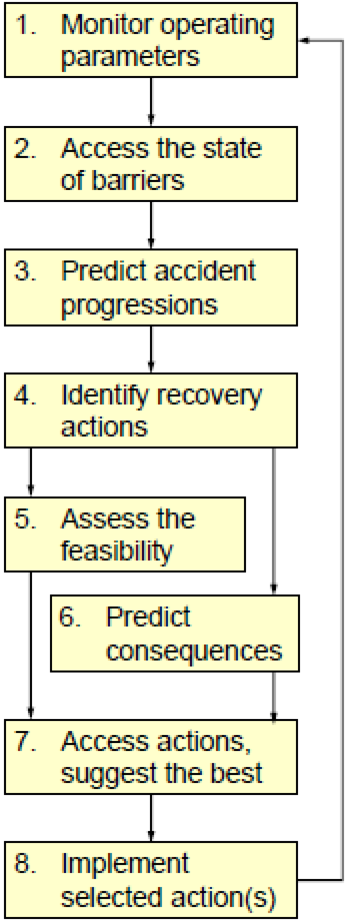
Decision-Supporting tool for Severe Accident Management (WP5)

Developing a demonstrative decision support tool for severe accident management, in order to make appropriate decisions in a timely manner.

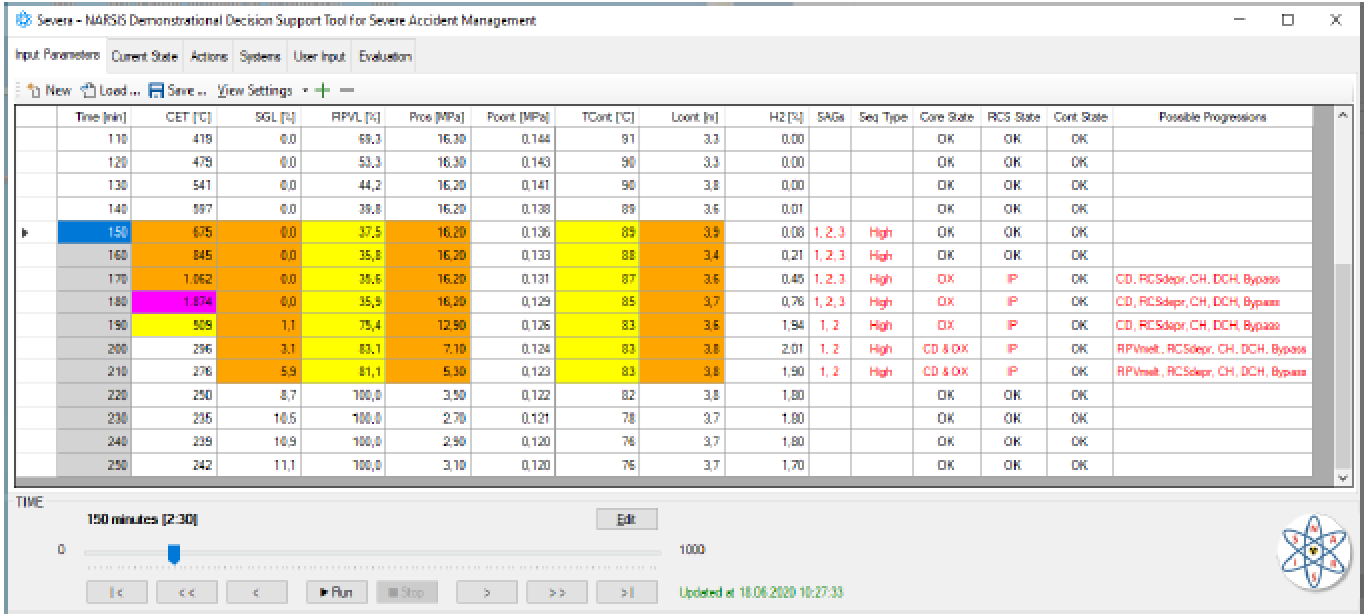
The tool SEVERA:

- interprets time series of measurements of important physical parameters,
- provides relevant information that would help to understand the state of NPP systems and possible development of the accident, and
- assesses possible consequences of management actions in terms of likelihood of radioactive releases to the environment.

SEVERA computer program



A number of simulations have been performed for Gen II nuclear reactor in order to predict possible progressions of accident.



Time [min]	CET [°C]	SGL [%]	RPVL [%]	Pres [MPa]	Pcont [MPa]	TCont [°C]	Lcont [m]	H2 [%]	SAGs	Seq Type	Core State	RCS State	Cont State	Possible Progressions
110	419	0,0	69,3	16,30	0,144	91	3,3	0,00			OK	OK	OK	
120	479	0,0	53,3	16,30	0,143	90	3,3	0,00			OK	OK	OK	
130	541	0,0	44,2	16,20	0,141	90	3,8	0,00			OK	OK	OK	
140	597	0,0	39,8	16,20	0,138	89	3,6	0,01			OK	OK	OK	
150	675	0,0	37,5	16,20	0,136	89	3,9	0,08	1, 2, 3	High	OK	OK	OK	
160	845	0,0	35,8	16,20	0,133	88	3,4	0,21	1, 2, 3	High	OK	OK	OK	
170	1.062	0,0	35,6	16,20	0,131	87	3,6	0,45	1, 2, 3	High	OX	IP	OK	CD, RCSdepr, CH, DCH, Bypass
180	1.874	0,0	35,9	16,20	0,129	85	3,7	0,76	1, 2, 3	High	OX	IP	OK	CD, RCSdepr, CH, DCH, Bypass
190	509	1,1	75,4	12,90	0,126	83	3,6	1,94	1, 2	High	OX	IP	OK	CD, RCSdepr, CH, DCH, Bypass
200	296	3,1	83,1	7,10	0,124	83	3,8	2,01	1, 2	High	CD & OX	IP	OK	RPVmelt, RCSdepr, CH, DCH, Bypass
210	276	5,9	81,1	5,30	0,123	83	3,8	1,90	1, 2	High	CD & OX	IP	OK	RPVmelt, RCSdepr, CH, DCH, Bypass
220	250	8,7	100,0	3,50	0,122	82	3,8	1,80			OK	OK	OK	
230	235	10,5	100,0	2,70	0,121	78	3,7	1,80			OK	OK	OK	
240	239	10,9	100,0	2,90	0,120	76	3,7	1,80			OK	OK	OK	
250	242	11,1	100,0	3,10	0,120	76	3,7	1,70			OK	OK	OK	

Conclusions

- NARSIS methodology has been implemented in an open-source open-access software tool, the NARSIS Multi-Hazard Explorer, proposing five successive levels for assessment, to be used as part of the steps related to Initiating Events and Screening (deterministic or probabilistic) analyses in extended PSA.
- The benefits of using multiple IMs (referred to as vector-valued IMs) for fragility assessment of SSC against single (earthquake) and multi-hazard natural events, were investigated.
- The methodologies and developments presented can all be used within a PSA. Each has advantages and disadvantages, and this work adds to the available tools which can be used to analyse and communicate on safety. Some methods (e.g. BNs) can be used as advanced versions of standard tools, whereas others can be used to investigate specific aspects and reduce uncertainties. Given the large variety of decision-making situations, finding a single appropriate framework appears to be debatable, and it is beneficial to take advantages of the strengths of multiple approaches to capture different types of information and knowledge important to inform decision-making.

Conclusions

- A novel model-order reduction technique was implemented for seismic fragility assessment: the Proper Generalized Decomposition (PGD), combined with the Large Time INcrement (LATIN) method, a general solving strategy for nonlinear problems in mechanics made of an alternative sequence of nonlinear and linear stages.
- SEVERA developed tool relies on the PSA techniques and current status of SAMGs for extensive damage and severe accident management. Its DM process can be divided into a typical operation cycle, starting with the observation and interpretation of the measured parameters, then continuing with the assessment of the plant systems state and the prediction of possible accident progressions, and finally ending with the formulation of possible management/recovery actions and the assessment of their effectiveness in terms of probabilities of radioactive release categories.