NARSIS

New Approach to Reactor Safety ImprovementS

WP6: Dissemination and Communication activities

D6.15 – Project Handbook

This project has received funding from the Euratom research and training programme 2014-2018 under Grant Agreement No. 755439.

Project Acronym:	NARSIS		
Project Title:	New Approach to Reactor Safety Improvements		
Deliverable:	D6.15 – Project Handbook		
Month due:	54	**Month delivered:**	54
Leading Partner:	BRGM		
Version:	V1		

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Dissemination Level		
PU	Public	**X**
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

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APET	Accident Progression Event Tree
BEPU	Best Estimate Plus Uncertainties
BN/BBN	Bayesian (Belief) Networks
CCF	Common Cause Failure
DBA	Design Basis Accidents
DEC	Design Extension Conditions
D-i-D	Defense-in-Depth
DSA	Deterministic Safety Analysis
E-BEPU	Extended Best Estimate Plus Uncertainties
EDG	Emergency Diesel Generators
ESD	Event Sequence Diagram
ET	Event Tree
FFTBM	Fast Fourier Transform Based Method
FT	Fault Tree
GLM	Generalized Linear Model
HEP	Human Error Probability
IE	Initiating Event
LOOP	Loss Of Offsite Power
MGL	Multiple Greek Letter
MLE	Maximum Likelihood Estimation
NPP	Nuclear Power Plant
PCD	Partial Cool Down
PGA	Peak Ground Acceleration
PIE	Postulated Initiating Events
PSA	Probabilistic Safety Assessment
PSFs	Performance Shaping Factors
PWR	Pressurized Water Reactor
RHR	Residual Heat Removal
SA	Spectral Acceleration
SAMGs	Severe Accident Management Guidelines
SCD	Secondary Cooldown
SBO	Station Blackout
SG	Steam Generators
SLIM	Success Likelihood Index Method
SPARH	Standardised Plant Analysis Risk-Human Reliability Analysis
SSC	Systems, Structures and Components

1 Executive summary

1.1 The Multi-Hazard framework

Existing safety analyses for Nuclear Power Plants (NPPs) are generally based on single external hazards in terms of the external loading of Systems, Structures and Components (SSC).

A **first key objective** of the NARSIS project, addressed within the **WP1**, was to provide a Multi-Hazard (MH) framework, quantifying and assessing primary and secondary hazards including cascading effects as well as uncertainty, in order to allow studying the consequences of combinations of potential well-characterised physical threats due to different external hazards and scenarios. In WP1, new approaches were proposed, focusing on some external hazards identified as priorities by the PSA End-Users community in the European ASAMPSA-E project: earthquakes, flooding, tsunamis and extreme weather. The final goals in WP1 were hence to: (1) develop such an integrated MH framework for nuclear safety assessment, accounting for single, cascade and combination events at different time scales and (2) give recommendations for regulators for use of the framework.

In WP1, it was important to determine which hazards are more attuned to probabilistic or deterministic analysis and where the improvements could lie in assessment. Often flood modelling uses a probabilistic basis whereas earthquake modelling uses a stochastic (event-based probabilistic) basis but much was learnt from the existing individual analysis of peril types. Key input parameters and metrics were examined for each of the main types, as well as how uncertainty is examined as part of the analysis framework. Uncertainty analysis forms a major part of any result given the large variability of past events and simply the random nature of natural hazards. The way each event is modelled changes depending on the hazard type and the situation. There are often many ways to model the same event with various trade-offs for speed, accuracy, precision and repeatability. These were examined too. Often these events will also produce secondary hazards (e.g. an earthquake-triggered landslide), thus for each hazard, the secondary effects were examined. By using the historical regressions and/or mathematical relations, the various frequency and correlations of each event to one another were produced.

As part of the MH framework works, the improvement of existing PHA methodologies (e.g. tsunami, extreme weather and flooding) was explored and for each of the single hazard curves, the NPP components were examined in order to ensure that relevant hazard parameters are provided for each hazard in the final framework. It was also decided to analyse all NPPs in Europe including decommissioned and research plants to examine potential sites for NARSIS analyses. Many historical single and MH events were reviewed and over 60 natural hazard events were identified as affecting NPPs in Europe, however with moderate damages in most cases.

The final 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 MHE software is suitable not only for multi-hazards but also for independent single hazards assessment. The proposed approach is very plant specific, and although the methodology can screen all hazard types and scenarios, there are still some combinations, which may be missed due to specific fragility loops, and/or dynamic hazard loops.

1.2 Fragility assessment

A **second key objective** of NARSIS, addressed in the **WP2**, was to develop refined fragility derivation methods in order to increase the accuracy of the estimation of SSC failure rates, thanks to current advances in quantitative hazard modelling and computational capacities. Quantifying the fragility of SSC w. r. t. a wide range of external loadings induced by natural hazards is indeed a challenge. To this end, fragility curves, which express the probability of an SSC to reach or exceed a predefined damage state as a function of an Intensity Measure (IM) representing the hazard loading, are common tools developed in the nuclear industry. Their probabilistic nature make them well suited for PSA applications, at the interface between probabilistic hazard assessments and event tree analyses, in order to estimate the occurrence rate of undesirable top events.

Due to the thousands of SSCs present in a NPP, most nuclear regulations advocate the application of Safety Factors methods, which consist in multiplying design level values with factors representing uncertainties due to capacity and demand variability. This approach has been used by practitioners since the 1980s, due to its relative ease of implementation when compared to time-consuming numerical simulations. More recently, the Risk-Informed approach has assumed a more relevant role in safety analysis as compared to the safety factor model: it focuses on the evaluation of the “probabilistic margin”, defined by the probability that the load exceeds the capacity.

The first step was to determine the **safety significance of the most critical SSC in NPP systems**, in order to focus on the components that deserve in-depth fragility assessment. The screening and selection process is based on risk-informed criteria using different quantitative importance measures, such as the Fussell-Vesely (FV) one or others depicting the change of the system unavailability when the contributor’s failure probability is set to 0 or 1 (e.g. the Risk Achievement Worth/Risk Increase Factor or the Risk Reduction Worth/Risk Decrease Factor).

Then, various numerical models and approaches were investigated in order to integrate **cumulative effects such as ageing and successive loadings or soil-structure interactions**.

Finally, 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. In case of MH scenarios, the approach relies on the combination of failure modes due to single hazard loadings and on the assessment of cumulative hazard effects on the studied systems, provided that the required hazard-specific physical models are available. The **integration of human factors** in the reliability analysis, as a potential source of epistemic uncertainty in the PSA, was also explored.

1.3 The Multi-risk integration framework for safety analysis

A **third key objective** of NARSIS, addressed in the **WP3**, was to improve the integration of external hazards and their consequences with existing state-of-the-art risk assessment methodologies in the industry. The approach taken was to investigate, further develop and evaluate different methods for safety assessment of NPP, following three main themes:

- Investigation of the use of **Bayesian Networks** (BNs), focusing on delineating the advantages and challenges as compared to more traditional probabilistic safety assessment techniques such as fault trees (FT);
- Development of the **Extended Best Estimate Plus Uncertainties** (E-BEPU) methodology and evaluation of its behaviour regarding defence-in-depth and design extension conditions.
- Developments in **constraining uncertainties**. Uncertainties remain in all probabilistic safety assessment, especially in industries characterised by high reliabilities and therefore have little data available on failures. Developments focused on the ability to identify the most influential sources of uncertainty and novel methods to reduce them.

As part of the focus on BNs, a step-wise, iterative framework for multi-hazard risk integration, using BNs, was presented. Vector-based fragility was used in order to use multiple IMs for hazards and a novel BN-based method for human error probability was developed and connected to technical BNs. In complex (sub-)systems, BNs were shown to be able to be used as surrogate models for advanced numerical methods, in order to substantially reduce computational effort and allow their inclusion into larger systems. In addition, a new approach to the analysis of common cause failures was developed showing several advantages over existing methods in both calculation of the impact and visualisation.

With the new developments for uncertainty characterisation, any practitioner of NARSIS is equipped with efficient sensitivity analysis tools to identify most influential sources of uncertainty and to set up prioritisation for reducing them. These developments, though dedicated to the specific aspects addressed within NARSIS, are of interest for any practitioners that are confronted with uncertainty analysis in safety assessments as shown by our applications to multiple and diverse real cases. In case of modelling of operator/human actions, the human failure probability for these actions can now be assessed and included in the study. Finally, a particular result is for the treatment of expert-based information using the tools of new uncertainty theories.

A detailed E-BEPU methodology was developed (in this WP) and its use demonstrated on the NARSIS (WP4) standard design plant model. E-BEPU is able to introduce stricter requirements on possible event sequences and avoid of possible cliff-edge effects, and allow relaxations for extremely unlikely sequences under certain conditions when these sequences can be treated as “practically eliminated”. Demonstration required an enormous computational effort that simply could not have been done few years ago due to limited computational capacities at that time. The contribution of the methodology was demonstrated through its application to the evaluation of Defence-in-Depth (DiD), Design Extension Conditions (DEC) and Severe Accident Management Guidelines (SAMG).

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.

1.4 Applying and comparing various approaches for safety assessment

The main objectives of NARSIS **WP4** were to: (1) propose possible modelling reduction strategies, which could be compatible with safety analyses and uncertainty assessment, and (2) test the applicability of the proposed multi-risk integration methods (BBN, E-BEPU) for the safety analysis of a simplified theoretical PWR NPP representative of the European fleet. The final goal was to discuss the pros and cons w.r.t. existing approaches, so that it can be integrated into the current PSA methodologies.

Regarding **modelling reduction strategies**, some **metamodelling approaches** were investigated. Two different methodologies have been proposed for **seismic risk assessment**:

- The first one is based on **Artificial Neural Networks** (ANN) for the construction of metamodels used to derive the relations between seismic IMs and Engineering Demand Parameters (EDPs) of the structures, thus accelerating the fragility analysis. Fragility curves can then be evaluated using direct Monte Carlo simulations by assuming a lognormal model and applying linear regression techniques. The methodology allows for vector-valued fragility curves. The ANN prediction uncertainty were also investigated and quantified. This methodology has been successfully applied to estimate the probability of failure of an electrical cabinet in a reactor building studied in the framework of the KARISMA benchmark.
- The second one is based on **Support Vector Machines** (SVMs) coupled with an **Active Learning algorithm**. This methodology adopts SVMs to achieve a binary classification of structural responses relative to a limit threshold of exceedance. Since the SVM output is not binary, but gives a real-valued score, a probabilistic interpretation of this score is introduced to estimate fragility curves very efficiently.

A metamodelling methodology based on **kriging** was also proposed for **earthquake-induced tsunami hazard assessment**, which is able to account for uncertainties on the scenario parameters (epicenter location, rupturing fault size, slip displacements). The kriging approach enables to learn in a nonparametric manner, the statistical link between the scenario parameters and the tsunami hazard IM, namely the maximum Sea Surface Elevation (SSE) at the coast. The kriging metamodels are used in place of some long-running simulations within a Monte-Carlo setting to evaluate the cumulative probability of SSE given the uncertainties on a worst-case scenario.

In parallel, 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. The PGD offers a conducive framework to obtain parametric solutions in the linear range.

When comparing the computational gain between the LATIN/PGD and some classical step-by-step integration methods (Newmark scheme for time integration and Newton-Raphson algorithm for nonlinearity), to evaluate the dynamic response of some structural components, with damaging quasi-brittle (e.g., concrete) or elasto-viscoplastic (e.g., steel) behaviours, it can be up to 700% in favour of the LATIN/PGD methodology. This latter is able to provide a parameterized solution, which can then be used for probabilistic studies (e.g. fragility curves derivation) at very low computational cost, by simply interrogating/interpolating the produced numerical charts.

Regarding the second objective, some reactor safety analysis for severe accident analysis, considering deterministic and probabilistic approaches

1.5 Supporting Decision-Making tool for Severe Accident Management

The **first objective** of NARSIS **WP5** was to develop a demonstration tool to support Decision-Making (DM) in the Severe Accident Management (SAM), to be used interactively by the TSC team, and based on a “referential” PWR plant (Gen II) where the level of critical systems and structures characterisation was sufficient for demonstration purposes. The selected referential NPP had two loops, large dry containment and safety systems for design basis, and design extension condition (DEC) accident management, including severe accidents.

The DM software tool developed in WP5, is called **SEVERA**. It is relying 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 (core, RCS and containment) 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. At the end of the cycle, the TSC team would be expected to decide which management action(s) to actually take, if any. A typical duration of such a cycle would be 10 to 20 minutes.

Hence, the SEVERA tool consists of two main parts:

- The diagnostic part is to establish basic facts about the status of the severe accident sequence, based on the feedback in the form of a set of pre-selected parameters.
- The prognostic part is to support the user in evaluating existing options / alternatives for accident management and mitigation, depending on the diagnosis and on the available means, and to select the best one or to rank the options / alternatives. Hence, this part does not interfere with the hierarchy or priority of the actions or instructions which are deterministically postulated in the SAMGs. It assists the user in identifying the actions which can be implemented under their predefined priorities, in a way which would result with the smallest risk from radioactivity release to the environment.

SEVERA is still a simplified tool which was developed in order to investigate the possibilities of this kind of support for DM in SAM, primarily for the training purposes of NPPs TSC staff. One of its most important limitations is about the treatment of time dependency of the probabilistic parameters incorporated in its prognostic logic. A number of phenomenological probabilities are presented by values which apply at an early phase of scenarios and, therefore, their use is limited to this time window. Furthermore, it relies on simplified presentation of logic models for “success paths” and system functions, as well as simplified consideration of adequacy of equipment included in the model and feedback from the implemented actions.

However, this demonstration version of SEVERA is capable of assessing the risk reduction potential of available mitigating actions based on expected time windows for equipment recovery and predetermined probability profiles of predefined major radioactive release categories for different plant statuses / configurations. The appropriate timely executed operator actions should reduce the early containment failure potential or/and minimize other types of radiological releases. The TSC staff decisions based on additional information and training with Severa can lead to better understanding and management of severe accidents in nuclear power plants.

A **second objective of WP5** was to apply the E-BEPU method in the development and V&V of SAMG involving the LB LOCA reclassification. Although the verification of the design of safety features provided for SAM is always a difficult task, E-BEPU allows for a feasible approach to such verification. It can provide additional insights that can be used for the development and V&V of SAMG, especially by identifying possible cliff-edge effects on one hand and by identifying very unlikely event sequences on the other hand that can be tolerated based on their unlikely occurrence, meaning that in some cases, they can be treated as “practically eliminated”.

2 The Multi-Hazard (MH) framework

2.1 Main objectives

WP1 has aimed at proposing new approaches for characterization of potential physical threats a nuclear installation can be exposed to, due 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.

The final objectives were to:

- Develop an integrated multi-hazard framework for nuclear safety assessment, accounting for single, cascade and combination events at different time scales;
- Provide recommendations for regulators for use of the framework.

These objectives were addressed within five main tasks and related main deliverables provided hereafter:

- Task1.1: Review of state-of-the art for hazard and multi-hazard characterization

  This resulted in deliverable D1.1 (Daniell et al., 2018).

- Task 1.2: Improvement of probabilistic hazard assessment (PHA) methodologies

  This task led to the following deliverables:

  - D1.2 (Gailler et al., 2020): Improved methodologies for tsunami hazard
  - D1.3 (Pheulpin et al., 2020): Improved methodologies for extreme weather and flooding hazard assessment, with hazard characterisation via multivariate statistical methods
  - D1.4 (Mokos et al., 2020): Flooding impact on industrial facilities via advanced numerical modelling
  - D1.5 (Daniell et al., 2020): Improved methodologies for extreme earthquake hazard assessment

- Task 1.3: Development of single and secondary effect hazard assessment methodologies and scenarios including uncertainty quantification and comparison

  This resulted in deliverable D1.6 (Daniell et al., 2019).

- Task 1.4: Production of an integrated hazard framework for combined hazard scenarios and software tool

  This resulted in deliverables D1.7 (Daniell et al., 2021) and D1.8 (Schaefer et al., 2021).

- Task 1.5: Recommendations for use of the integrated multi natural hazard framework for regulators

  This resulted in deliverable D1.9 (Halfon et al., 2022).

A synopsis of the key findings of each deliverable can be seen in the workflow of Figure 1 and will be further detailed in the next sections, showing the limitations and integration in the multi-hazard framework, software, and recommendations. The integration of aspects of the first 6 deliverables was used within the multi-hazard framework, either including methods, datasets, modelling, or lessons learned. This has then been integrated into the software and then recommendations were made for regulators from this WP1.

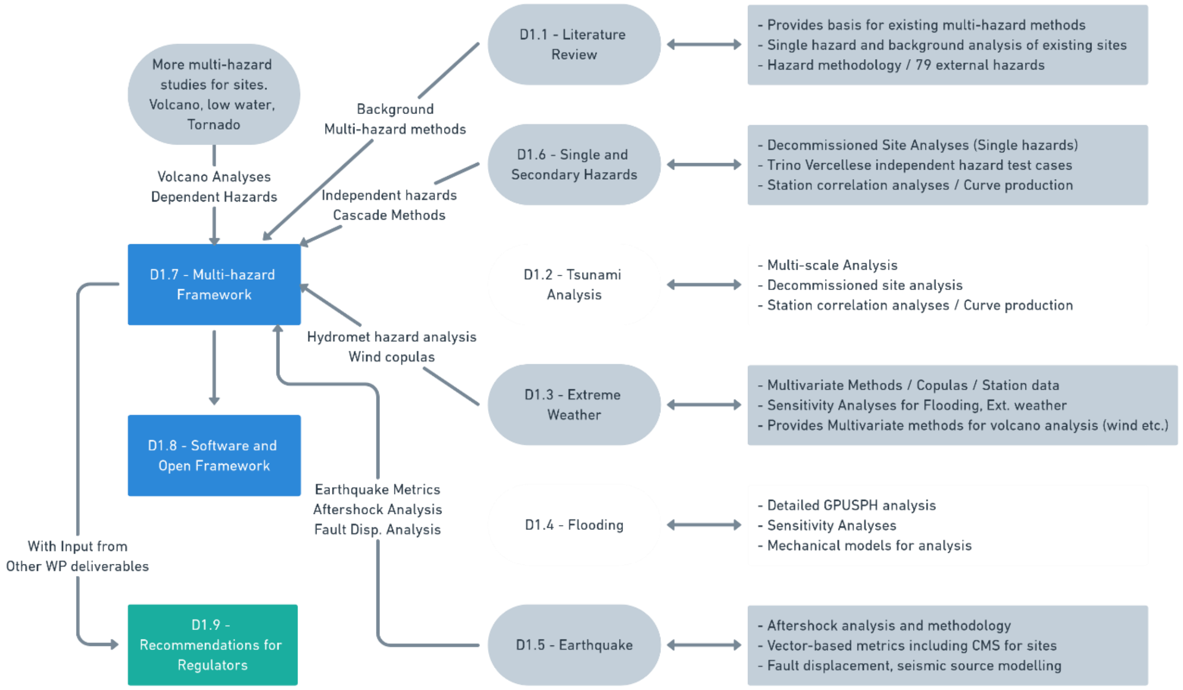


Figure 1: Multi-hazard framework and workflow of parts and concepts within WP1

2.2 General outcomes

As part of the MH framework WP, a state-of-the-art was undertaken in deliverable D1.1 (Daniell et al., 2018), to incorporate various facets of methodologies for single and multi-hazards, past disasters, stress test reviews as well as various definitions of natural external events (e.g. occurrence of concomitant external events, either simultaneous-yet-independent hazards or cascading events).

The definition of the inventories and definitions of the physical and operating fragility of main SSC (Systems, Structures, and Components) present in NPPs were part of deliverable D2.1 in WP2, and approaches to integrate the external hazards outputs with the comparison of risk integration methods from high-risk industries has been undertaken in WP3 (D3.1) with a particular emphasis of methods incorporating low probability events, multi-hazard frameworks and previous lessons learned, with insights into the potential better risk integration to be explored through Bayesian Belief Networks (BBN).

Here, it was decided to analyse all NPPs in Europe including decommissioned and research plants to examine potential sites for analysis.

Many methodologies, software packages, and datasets have been developed globally over the last decades for both probabilistic and deterministic hazard analysis of natural catastrophes. These tools have fed the production of potential external hazard scenarios and return periods for NPPs as part of Probabilistic Safety Assessment (PSA) and Screening analysis.

A huge amount of external hazards from natural catastrophes exist – over 70 as determined by the ASAMPSA-E project of geophysical, meteorological, extra-terrestrial, biological, hydrological, and climatological origin. These hazard types can occur singularly with direct or indirect impacts upon NPPs or as various multi-hazard scenarios. Some natural hazard types are directly influenced by other ones either directly via inducing the second hazard, or due to a common root cause (causally correlated), and some have little correlation with the others (i.e. volcanoes with heatwaves) and indeed some are mutually exclusive (i.e. high water level and low water level). Coincidental hazards are events that occur simultaneously but are independent. Indeed, each of these hazard-type interactions needs to be examined in a multi-hazard assessment. Definitions of these were used from ASAMPSA-E (Figure 2), Tilloy et al. (2019, see Figure 3), and Gill and Malamud (2014) among others. The definition of hazards was the first important step to characterising which potential events could impact NPPs. A very important concept associated with each hazard was the duration of each event.

Many historical single and multi-hazard events have been reviewed as part of this work, including large events such as the Tohoku 2011 earthquake and tsunami which will have a long-lasting impact on the nuclear industry. Over 60 natural hazard events were identified affecting NPPs in Europe but in most cases, the damage was not extensive. However, many more events not affecting NPPs were identified from history. In fact, for earthquakes, 30% of all fatalities have not been from shaking but from secondary effects such as tsunami or landslides. Similarly, we often see for tropical cyclones that storm surge and rainfall cause more fatalities than the pure wind losses themselves. Such events are important for calibration of any NPP multi-hazard assessment.

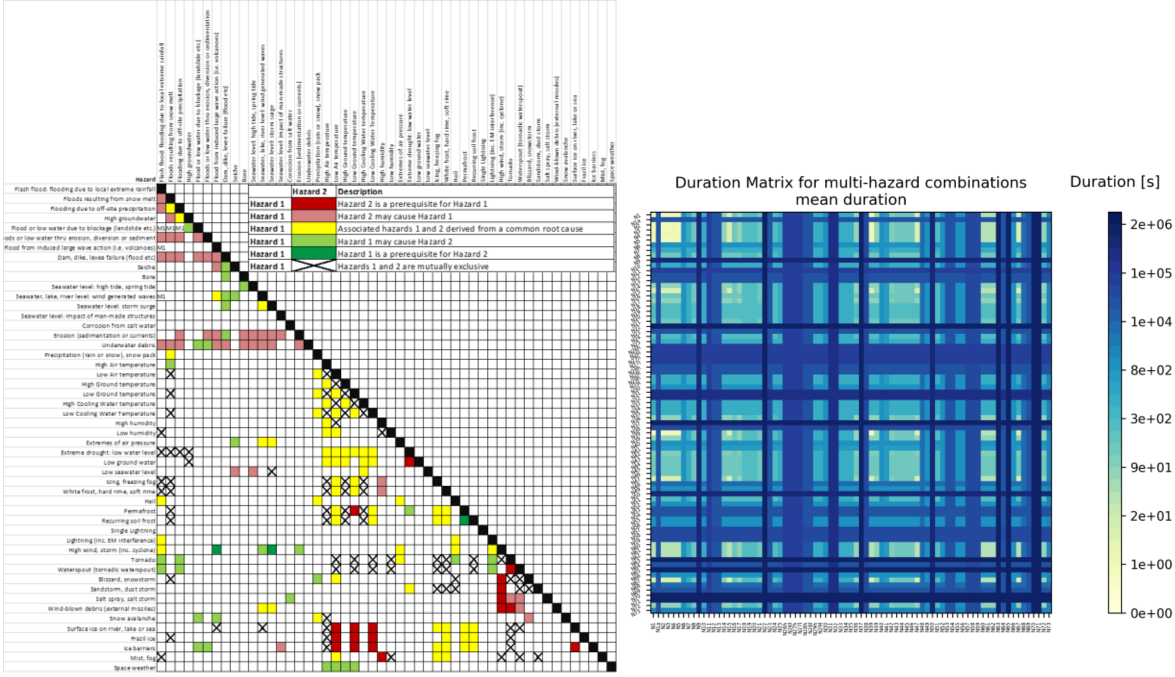


Figure 2: (Left) Extreme Weather correlation matrices of all primary, secondary and tertiary hazards, as well as (Right) Mean pairing duration (mins), the X and Y labels indicate the cross-correlation of the hazards which are detailed in Annex B spreadsheets from N1-N73 in line with an adjustment of the ASAMPSA-E definitions.

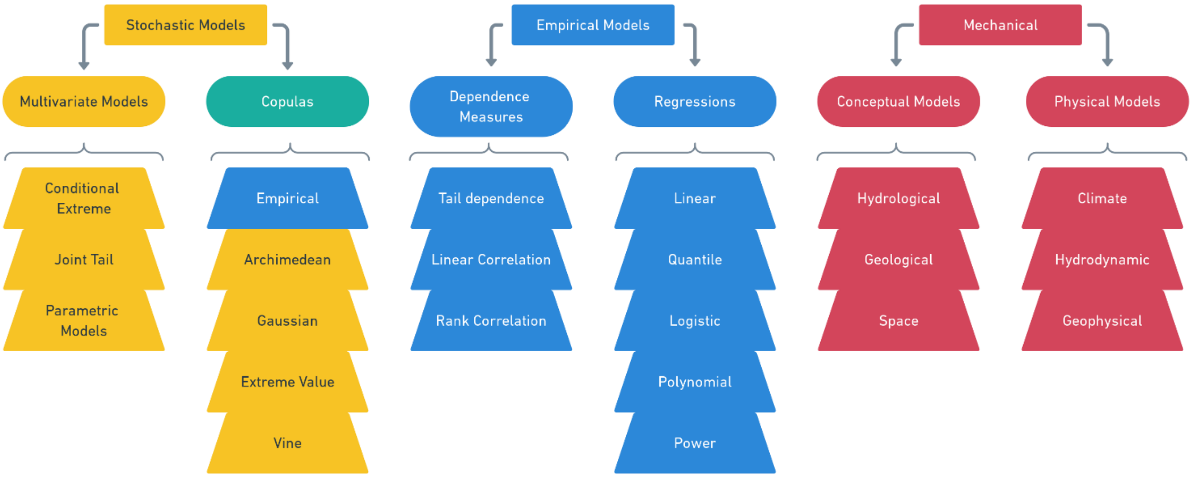


Figure 3: Stochastic, empirical and mechanical models after Tilloy et al., 2019.

A review of the stress tests for European NPPs showed the key design parameters for earthquake, flood, and precipitation, using the national and individual plant reports for each of the available NPPs in Europe. The multi-hazard aspects, however, are not touched upon in nearly all cases, thus the need for this project (Haecker et al., 2019).

For the key hazards identified to affect NPPs across Europe, earthquakes, tsunami and waves, extreme weather effects (heat/cold wave, hail, precipitation, etc.), and flooding, empirical data for Europe has been collected and examined as well as a discussion of empirical events collected from various scientific papers, projects and industry briefs (Daniell et al., 2018). Methodologies have been put forward for the state-of-art assessment in deterministic or probabilistic methodologies for the perils be it via extreme value statistics of empirical data, with Monte Carlo simulation to produce a stochastic event set; or PSHA using historical regression of earthquake data via seismotectonic zones and lognormal relations (or forms of it). Various projects were reviewed such as PEGASOS for NPPs in Switzerland (see http://www.swissnuclear.ch/de/downloads.html), which shows an example of a fully probabilistic framework for earthquake hazard assessment using a full logic tree approach. The task included a review of terminology and characterization for hazard assessment concerning nuclear safety as well as provided sources for data input later in the project. The new EU-SHARE project has also been examined among many others such as the RAIN project.

In WP1, it was important to determine which hazards are more attuned to probabilistic or deterministic analysis and where the improvements could lie in assessment. Often flood modelling uses a probabilistic basis whereas earthquake modelling uses a stochastic (event-based probabilistic) basis but much was learnt from the existing individual analysis of peril types. Key input parameters and metrics have been examined for each of the main types, as well as how uncertainty is examined as part of the analysis framework. Uncertainty analysis forms a major part of any result given the large variability of past events and simply the random nature of natural hazards (D3.3 and D1.6). The way that each event is modelled changes depending on the hazard type and the situation. There are often many ways to model the same event with various trade-offs for speed, accuracy, precision and repeatability. These have been examined. Often these events will also produce secondary hazards (such as an earthquake inducing a landslide), thus for each hazard, the secondary effects have been examined. By using the historical regressions and/or mathematical relations, the various frequency and correlations of each event to one another were produced.

All this analysis needed to be done in a software framework, thus open-source and open-access software packages from around the world for each peril have been examined, as to their ability to model single perils, and the production of singular and combined hazards (e.g. high winds or earthquake & high precipitation leading to structural damage and equipment flooding) and cascades (earthquake with fire-following or flooding-following due to damaged spent fuel pool or pipes, etc.) but also the potential impact on supply and infrastructure (road access, power supply, water supply, etc.) in which the NPP is embedded and on which its functionality depends. Very few software packages deal with multi-hazard, and none of the available software packages deal directly with such an event tree, with a few such as OOFIMS, HAZUS, Riskscape, CLIMADA and CAPRA providing a first step to the combination. The sensitivity of the model assumptions creating the hazard curves has been gleaned. The step from single to multi-hazard analysis and the review of various frameworks suggested that this field is rapidly evolving with a significant increase in literature associated with multi-hazard in the last 5 years (in part due to the Tohoku event).

Various methodologies such as multivariate analysis and multi-hazard scenarios and combinations of curves have been undertaken by many authors at a global, regional and local scale. These have been detailed from over 50 authors in D1.1 and D1.6. However, there has as yet been no significant study dealing with an empirical-analytical hands-on approach for NPPs, with ASAMPSA-E providing some background but no model.

The 3-level framework of MATRIX with qualitative, semi-quantitative and quantitative analysis, provided a first step as to a framework which could be potentially used for NPPs. By adding some of the aspects of the model by Liu et al. (2015), examining various triggering mechanisms and the feedback loop of other authors (Zaghi et al., 2016), this provided the basic tools to do multi-hazard analysis for NPPs in NARSIS.

With respect to NPPs, it can be seen from the stress test review and some other details that correlated hazards have rarely been used as part of design, however using the frameworks found, this allowed for the production of a software based on tasks 1.2, 1.3 and 1.4, and the software review as part of this analysis.

Each country has its own regulatory requirements regarding the consideration of external hazards in a probabilistic context however within WP1, the focus resided on the European requirements. The state-of-the-practice analysis of external hazards satisfies the Western European Nuclear Regulators Association (WENRA) safety expectations (see e.g. WENRA, 2015).

The final methodology proposed in NARSIS is based on the MATRIX approach (Liu et al., 2015), with complements and adaptations for the NPP specific nature. The framework includes five successive levels (see details in D1.7):

- 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

Figure 4 gives an overview of the various pathways for analysis of multi-hazard scenarios in the NARSIS framework (Level 1 to 4), whereas Figure 5 shows a flow chart for extended PSA with the proposed location of the multi-hazard framework component.

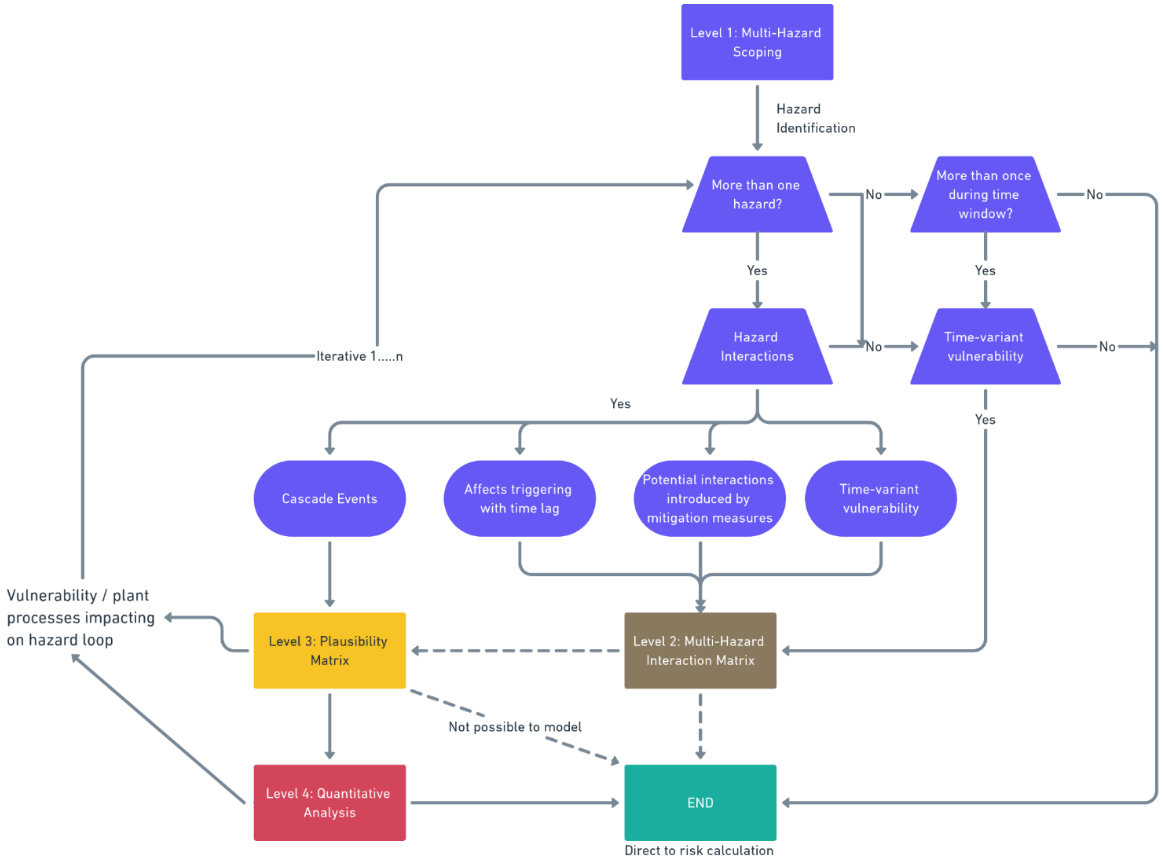


Figure 4: The multi-hazard framework with the various pathways possible in terms of analysis of multi-hazard scenarios for input into PSA.

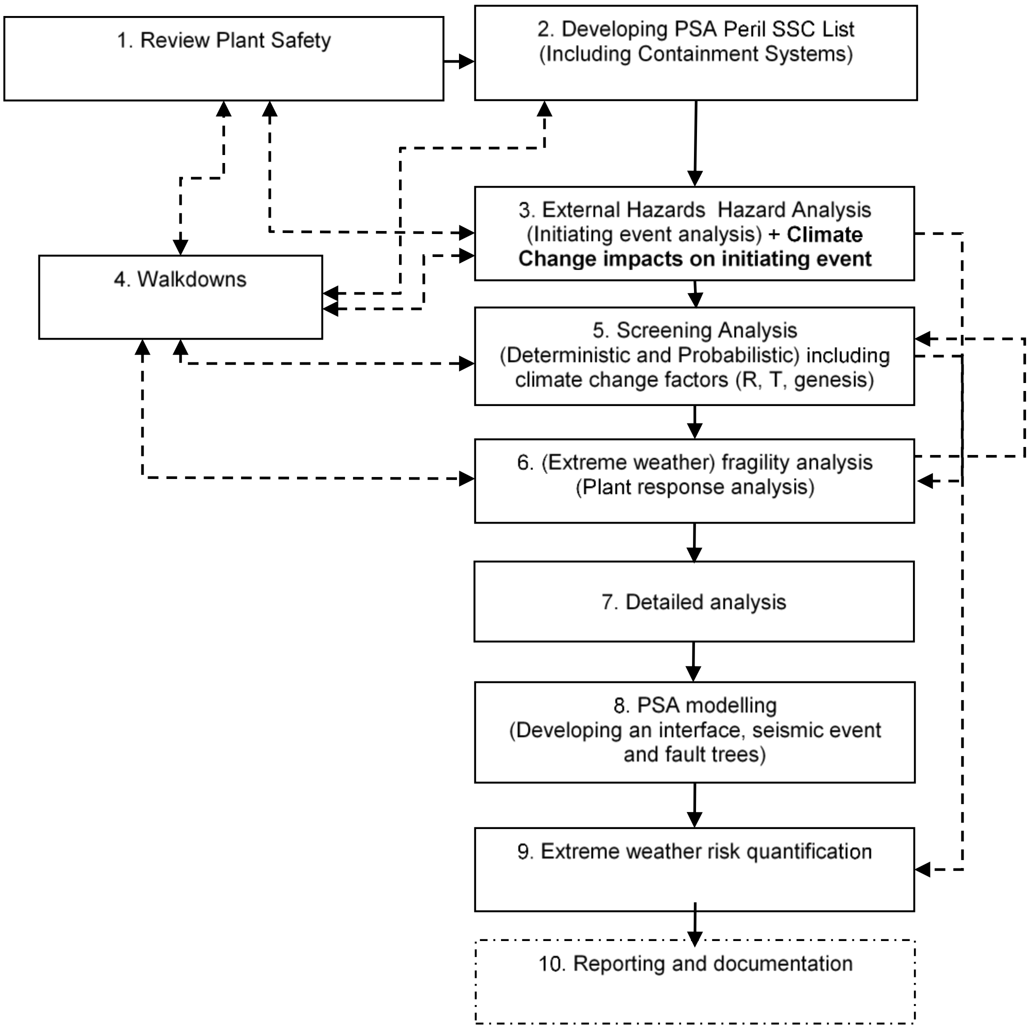


Figure 5: Flow chart for extended PSA showing the proposed location of the multi-hazard framework component incorporating the multi-hazard framework as part of Parts 3 and 5.

2.3 Testing and refining the Multi-Hazard (MH) framework

The choice of sites around Europe was important with much care taken as a NPP would not make sense to be sited anywhere, and thus creating a generic set of locations was considered outside of the scope of this project. Using decommissioned and shutdown sites derived from this study, allowed for a large testbed for hazard curves without any political issues with assumptions made for research purposes. Certain plants were removed as part of the analysis. A large amount of data has been scoped as part of this study for collecting site information. This was used to refine the single hazard curves during the course of the project and in order to account for multi-hazard combinations.

A collection of hazards datasets for Europe for the sites was examined to identify what was available for each of the hazards (Table 1). These datasets were characterised including their resolution and what can be used for the analysis. A preliminary data analysis and examination has been made for earthquake (and secondary effects), tsunami, flood, hail, lightning, tornado, rainfall, temperature, volcano and wind; including screening.

Table 1: Overview of hazard developed for each site

Site	**Latitude**	**Longitude**	**Earthquake**	**Flood**	**Tornado**	**Lightning**	**Hail**	**Volcano**	**Wind**	**Temperature**
Trino Vercellese	45.18313	8.27677	X	X	X	X	X	X	X	X
Mülheim Kärlich	50.40799	7.48592	X	X	X		X	X	X	X
Biblis	49.70879	8.41449	X		X			X	X	X

The detailed analysis of site location hazard curves and analysis has been presented:

(1) Hazard curves have been produced for Trino Vercellese in Italy as well as Mülheim-Kärlich and Biblis in Germany for earthquake including curve and disaggregation. The conditional mean spectrum method was used in order to provide adequate and representative time histories.
(2) Flood hazard was examined at sites including Trino Vercellese, Mülheim-Kärlich, Obrigheim, Biblis in order to create hazard curves and provide input. Flow data from stations was also examined as well as resolution of data.
(3) Station correlation analysis for extreme weather was undertaken as part of the study, with the examination of temperature, wind, and rainfall made for various stations. The station data around Europe was audited, and some examples for key sites were provided.
(4) Multivariate modelling was also undertaken looking at the correlation between various dependent parameters/station measurements.
(5) In addition, less common hazards such as volcano were examined for these main sites.

The preliminary hazard curves produced as part of this study were for four main sites, however, the European datasets sourced as part of this study, enabled plausible hazard curves to be derived for all of the decommissioned and shutdown sites.

These hazard curves and knowledge were included within the software setup for the first four hazards and sites. The software presented the single hazard curves for the various chosen sites, including different hazard parameters where applicable and were checked with WP2 and WP3 in order to ensure that the hazard curves as well as parameters were compatible with their outputs.

For each of the single hazard curves, the NPP components were examined in order to ensure that relevant hazard parameters are provided for each hazard in the final software. However, for the hazard curves, it was also needed that the state-of-art and also innovative solutions are used as part of the framework.

This was done through 4 deliverables (to D1.5), which explored the improvement of existing PHA methodologies, respectively for tsunami (D1.2), extreme weather and flooding (D1.3), detailed scale flooding with GPUSPH (D1.4) and earthquake (D1.5).

The key aspects regarding the improvement of PHA methodologies for the MH framework are recalled in the following sections.

2.3.1 Development of Probabilistic Tsunami Hazard Assessment approaches

Within D1.2 (Gailler et al., 2020), it was seen that the management of the tsunami hazard can be done dealing with two time-scales:

(i) the warning time-scale which starts with a triggering event in real time such as an earthquake and
(ii) the historical time-scale with the study of past events and the extrapolation to future events looking for the worst probable scenarios (Deterministic Tsunami Hazard Assessment: DTHA) or using Probabilistic Tsunami Hazard Assessment (PTHA).

DTHA appears as the most conservative approach and was used in most of the forecasting tools in operational context. PTHA has the advantage to better target the most affected regions and to determine the most dangerous sources for a chosen region and a return period. PTHA aggregates numerous scenarios in order to take into account various sources of tsunamis (location and intensity). The results of PTHA can inform on the most impacted places (depending on the region of interest) but also where the most impacting sources are located. European scale results were examined.

Most of studies relying on PTHA use regional PTHA approaches, that means PTHA was computed at basin scale (offshore) only, to reduce the computational cost. Then PCTAs are obtained from empirical amplification laws such as Green’s laws (e.g., Grezio et al. 2020), which is ten times faster than a complete high resolution modelling, but provides a crude approximation of wave heights at the coast only within a factor of 2 at best (e.g. Gailler et al, 2018). Moreover all local effects were not taken into account (e.g. resonance in harbours) and the assessment of run-up and horizontal inundation were missing.

The PTHA approaches developed in NARSIS were based on an accurate numerical tsunami propagation and inundation modelling by using several nested bathymetric grids, characterized by a coarse resolution over deep water regions and an increasingly fine resolution close to the shores (down to 10m resolution in the French Riviera test-site). Thus, specific coastal responses (i.e. resonant harbours effects and sharp transitions of the seafloor, marine infrastructures impacts, dispersive effects,…), and run-up and horizontal inundation computation were assessed properly. The availability of high resolution bathymetry/topography grids along the coastlines is thus a compelling factor using such an approach

The whole process to compute the PTHA includes many uncertainties, which have to be integrated into the approach. In particular, the list of earthquakes to calculate the distribution law and the list of unity faults of the fault system to create the rupture catalogue were not exhaustive. The uncertain distribution of the fault slip, especially in near field context, can also have a significant impact on the nearshore wave propagation. This needs to be taken into account, as shown by the stochastic slips study of rupture scenarios performed on the 1755 Lisbon tsunami case, where the impact of the slip variability on the tsunami wave height was analysed via a metamodeling technique. Indeed, the slip heterogeneity can induce a large variability of the wave height. Neglecting such a variability can lead to a severe underestimation of the wave height for near-field sites.

Further study would be needed to analyse the full spatial maps of the maximum water height (not only at some sites as done in D1.2), in order to highlight directly the link between fault slip patterns and wave amplification patterns. Further study will also be needed on the effect of an uncertain tidal level to the tsunami wave but for D1.2, the use of the software was shown.

In addition, the tsunami work showed that a much higher computational speed achievable with GPUs allows for a probabilistic treatment of uncertain slip distributions in fault models.

2.3.2 Extreme weather and flooding: hazard characterisation via multivariate statistical methods

Within D1.3 (Pheulpin et al., 2020), a number of methodologies were presented for potential use within PSAs within Europe looking at extreme weather and flooding. When looking at multi-hazard, the duration of the events is extremely important in terms of their potential impacts when overlapping or coinciding hazards are analysed. Durations and correlation matrices were re-examined as part of this deliverable.

We are likely to miss important information if we only estimate return levels (or equivalent metrics) focusing on the instantaneous severity of events. Several available approaches were outlined which were to use information about the duration of events, in order to improve natural hazard assessment. In NARSIS, we have focused on approaches from within the class of extreme value models, as these are models with mathematical justification for extrapolating beyond the range of the data and are the most commonly used approaches for this type of analysis within the nuclear industry.

In terms of standard approaches for the application of climate change results to NPP design, guidelines have been put forward in various forms. PRIMAVERA-H2020 was the latest EU project to provide high resolution analyses on a smaller scale appropriate to NPP site levels. This downscaling and higher resolution allows for a better application of possible effects of climate change. As the PRIMAVERA models and other downscaled models become available at a reasonable resolution, they should be integrated in conjunction with the usual station data which is usually collected at the site, and from long-run stations around the site.

At present, structural design codes are based on the assumption of stationary climate conditions. The reliability targets are typically specified or understood in terms of the annual probability of failure over the design life of the structure, typically 50 to 75 years. In the reliability-based design framework, the nominal design loads are specified in terms of return period or an upper percentile, e.g., 95th percentile, of the annual maximum load distribution. Further, load factors are specified to calculate the factored design load. The load factors are calibrated with respect to the target reliability level (i.e. annual probability of failure).

As the climate change effects are becoming evident, national code authorities are interested in evaluating the effect of non-stationary climate conditions on the structural design provisions. More specifically, it is being recognized that the reliability-based calibration approaches used under the traditional assumption of stationary climate condition cannot be directly extended to non-stationary climate cases. For example, the concept of return period is not applicable to non-stationary climate, as the distribution of the time between occurrences of the load events is no longer invariant. Similarly, the annual probability of failure is no longer constant in the non-stationary climate. A technical discussion has hence been developed in NARSIS and such issues, addressed using the theory of stochastic processes.

The assessment of external hazards, such as flooding or earthquakes, often relies on numerical models which allow assessing the variables of interest (e.g. water depths, ground acceleration, etc.). However, these models are affected by uncertainties which can be quantified through Uncertainty Quantification (UQ) and Global Sensitivity Analysis (GSA) studies. The UQ attempts to describe the whole set of possible outputs considering the inputs not perfectly known. The GSA aims at determining the most influent inputs to an output behaviour, as the non-influential ones. These two types of analyses are complementary and both classically suppose the input parameters of the numerical models are independent. Most literature studies consider the inputs independent which may not be the case. In D1.3, a global review of the different methods used for UQ and GSA with model inputs considered as dependent, has been performed and applied to hydraulic studies, to fill this gap in the field of flooding hazard. Interested readers can read IRSN reports on existing UQ and GSA methodologies for dependent inputs and an application to a simplified inundation case (Bacchi et al., 2019; Pheulpin, 2020), as well as a published research paper on the application of these methods to a large hydraulic model (Pheulpin et al., 2020). Some of these results have been presented in the EGU (Pheulpin and Bacchi, 2020).

The main results of the NARSIS works on extreme weather and flooding can be summarized as follows:

- There is a strong dependence between the hydrograph parameters and this dependency can be taken into account by using copulas.
- The use of metamodels is very useful for uncertainty analysis studies with limited computation resources.
- We have found a limited impact of inputs dependency in UQ.
- The duration and time to peak inputs have strong influence on the outputs.
- The hydrograph shape should not be ignored in hydraulic studies.

In NARSIS, we have shown the various benefits of using outputs from a multivariate extreme value model, to improve upon standard univariate extreme value analysis techniques, these latter requiring declustering to be undertaken in order to extract independent peaks over the threshold (POTs). We can summarize the benefits as follows:

- More of the available data information can be used, e.g. , exceedances which are not peaks but are still extreme. Since data has not to be declustered, there is no need to pick a declustering parameter (e.g. the run length), which is a subjective choice.
- Fitting the model in the Bayesian framework permits to estimate the predictive return level which rolls all uncertainty about the parameters and randomness in future observations into a single estimate.
- Standard frequentist approaches with declustering lead to higher estimates than the Bayesian posterior and predictive estimates. Uncertainty estimates for the fits to POTs are wider than those using the Bayesian approach.
- The subjective choice of declustering parameter (here the run length) can have a large impact on the best estimates and uncertainty intervals.

Finally, it is important to note that the work has focussed only on a few of the key issues listed by the ASAMPSA-E for extreme weather analyses, and this field is continuing to evolve and requires more work in the coming years to address the other issues listed, such as:

- Limitations in modelling and forecasting the physical phenomena and conditions leading to extreme hazard;
- Uncertainties in estimation of the impact of climate change on extreme meteorological events;
- Lack of site-specific data and limitations of spatial modelling and downscaling methods;
- Difficulties in quantification of uncertainties for common-cause failures;
- Difficulties in integrated modelling of hazard internal and external impact assessment;
- Limitation in determining the occurrence frequency of extreme weather conditions;
- Correlation among an extreme weather event induced failure modes and on the quantification of correlation coefficients.

The complexity of extreme weather and flood modelling as well as the non-stationary nature and lack of data make analysis difficult with major uncertainties.

2.3.3 Flooding impact on industrial facilities via advanced numerical modelling

Within D1.4 (Mokos et al., 2020), works aimed at demonstrating the ability of some new computational methods to perform extreme flooding impact prediction in decent computational time, compatible with nuclear safety studies. Here, the GPUSPH code, developed by an international consortium including EDF, was successfully used to simulate complex geometries for different cases with long runtimes on multiple GPU cards (Mokos et al., 2020):

(1) *Experimental wave tank with a complex dike geometry:* The GPUSPH simulation was used to measure regular wave overtopping and to compare with the experiments conducted at EDF. Good agreement with the experimental results was demonstrated for both overtopping volume and free surface position including the complex flow between the two ‘dikes’. Topics such as the creation of the simulation domain and the selection

of SPH parameters were investigated, which will be helpful for future use in addressing similar flows with GPUSPH. Potential improvements on these results can be achieved by solving the wave decay issue. The suggested method is the implementation of kernel renormalisation functions, the δ-SPH approach or an Arbitrary Lagrange-Euler model in GPUSPH.

(2) *Realistic coastline:* A realistic topography including the bathymetry of the surrounding area was modelled, considering first a low-resolution, altered version of a real coastline and investigating water overtopping a land strip. Overtopping was observed after continually increasing the wave height. However, the volume was insufficient to clear the entire land strip with only residual water pools remaining on it. The case was executed on a 350m x 350m domain for 100s of physical time with particle size of 0.05m.

(3) *Scaled model of a dike:* A dike model used for experiments was also simulated, considering a scaled domain of 22m x 20m (actual domain: 1584m x 1440m). The experiment considered separate cases regarding storm surges and wave heights, focusing on a case investigating conditions beyond the baseline similar to the ones that caused the Fukushima incident on 2011. The free surface position was assumed to be 9.29 m NGF, conforming to the framework of a study carried out after the Fukushima incident. The considered real wave height was 9.3 m with a period of 13s, which corresponds to the expected 100-year wave usually taken into account by offshore structure designers, with a 70% statistical probability.

   a. *Storm surge conditions (i.e. increased free surface height with regular wave train)*: As the dike model scale was 1:72, the associated wave height and period in the simulations were respectively scaled to 0.129 m and 1.5294s.The simulation took up 14 days for 60s (corresponding to 510s of real time). Coarser resolutions were simulated up to 100s. Overtopping was observed at the dike, similar to the experiment and the water volume in the troughs qualitatively matched the behaviour at the beginning of the experiment.

   b. *Solitary waves (tsunami approximation):* Both a solitary wave with the 100-year wave height and a wave with three times this height were tested. The results were similar to the regular wave train with the main reactors being unaffected by the impact, which was absorbed by the dike.

The advancements in GPUSPH v5.0 showed that its use is feasible for large-scale projects as it scales well with the use of more GPU cards. Regular wave trains in the dike case required about 25 minutes per wave period for a particle size of 0.025m. This was increased to about 60 minutes for 0.015m and about 300 minutes for 0.009m. For solitary wave cases, this means that multiple simulations can be executed in the same day.

The dike case also shows that scaling is a promising way for SPH to deal with larger domains. This would be beneficial for future examinations of the coastline case, where only part of the domain was simulated.

D1.4 also demonstrated the optimal SPH parameters and methods to improve runtime on large cases without sacrificing accuracy, where possible. The new pre-processing SALOME module for GPUSPH was tested and used to create the realistic topography domains. A trained user is estimated to need 2-4 days, depending on the required resolution to build a new case if a point cloud is provided. Best practices have been listed both for the module and for creating a mesh of sufficient quality.

Some shortcomings can be identified. The pre-processing module could still be improved, as it is still prone to crashing rather than adapting when faced with an anisotropic mesh. And while the computing performance of SPH has been improved, it is still computationally expensive for cases requiring both fine resolution and simulation of multiple minutes of real time. Variable resolution may significantly reduce computational times in the future (option does not exist in GPUSPH v5.0); the fast progress on GPU capabilities will also help.

2.3.4 Extreme earthquake effects

Earthquake ground motion from an extreme event can have aggravated implications if viewed in the context of accompanying phenomena such as tsunami and aftershocks. The key parameters along the process of European seismic hazard and the characterisation of interactions between different geophysical hazards in terms of earthquake interactions and correlations with other hazards (using ASAMPSA-E project as the basis) and duration of geophysical hazards were examined.

Within D1.5 (Daniell et al., 2020), a number of the key limitations w.r.t. earthquake hazard assessment for decommissioned NPPs in Europe have been explored, examining the previous hazard assessments done and examining some of the key differences w.r.t. the German cases. Given the large amount of literature in this field, a key focus has been made on some more innovative and improved analyses for various topics. Here we see that much insight is needed into the:

- Maximum magnitude (Mmax) assumptions associated with low seismicity locations,
- Earthquake catalogue cleaning and uncertainty calculations of major events including magnitude conversions,
- Seismotectonic zonation,
- Declustering methodologies,
- Seismic source models from offshore, nearfield sources.

Then, some selected key secondary hazard types in terms of aftershocks and fault rupture have been examined as well. Liquefaction and landslide require very specific site data, thus the methodologies have not been explored in D1.5.

In terms of fault rupture and displacement, the possibility of fault rupture at a site given a certain magnitude event is required, and can often only be defined via scaling relations. Probabilistic Fault Displacement Hazard Analysis (PFDHA) is generally undertaken. The latest datasets were discussed as part of this section including the key issues with uncertain sources. A quick study into fault displacement potential as well as the current seismotectonic fault state-of-art in European conditions was done, given the need for such knowledge in the wake of events like the 2016 Kaikoura earthquake in New Zealand where 24 faults ruptured in one sequential earthquake causing mixtures of ground shaking at respective sites. The assumption of various fault models as well as the scale of different models has been critically examined.

The damaging potential of aftershocks with lower ground motion but high probability of occurrence have been analysed and models developed that can interact with fragilities of intact structures and components, and subsequently modify these fragilities via the impact of the ground shaking of the main event and evaluate the probability of exceedance of limit states for the subsequent aftershock activity (for Japanese earthquakes see Goda et al., 2015).

Here, there is also a link to the tsunami work produced in D1.2.

The challenge was to define a design ground motion in terms of return periods which take the primary and secondary effects (aftershocks, tsunami) into account. The characterisation of aftershocks in terms of duration is key for the definition of interactions for operational time windows after earthquake events. In addition, earthquake forecasting methodologies were discussed as background, given the potential use for operational time window definition, or within certain parts of the pre-seismic chain.

A short synopsis of physics-based stochastic approaches for ground motion simulations (SGMSM) from Otarola et al. (2016) and Bayless and Abrahamson (2019), and the illustration of their potential use has been produced as well.

The UHS (Uniform Hazard Spectrum) generally being the more conservative option for the selection of the input ground motions, the CMS (Conditional Mean Spectrum) has not been widely used in NPP settings, although this approach leads to site-specific fragility functions, which are well suited to the context of NPPs. However, the use of a CMS is important in terms of potential scaling factors of the spectra as well as for not overestimating along the entire chain of the PSHA. In D1.5, two different CMS analyses have been performed and compared for similar settings.

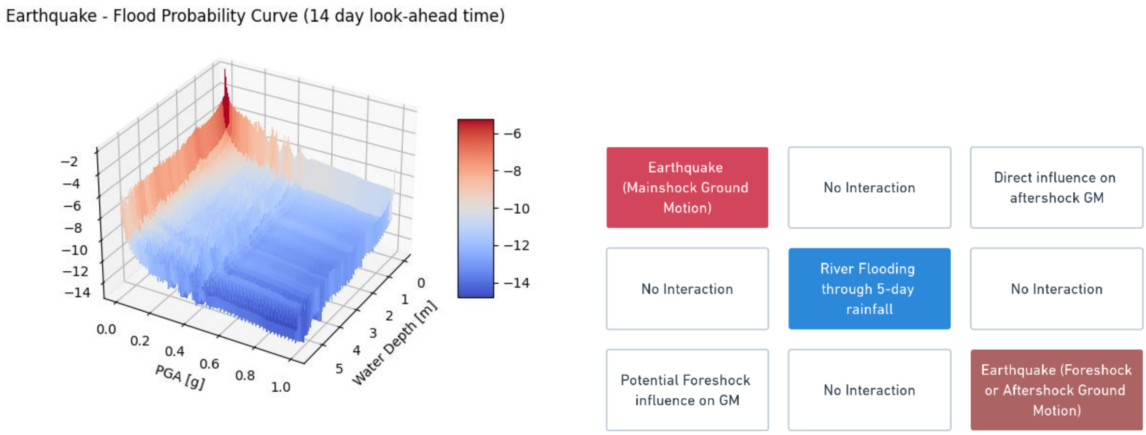
The first step before being able to move towards a risk-targeted hazard definition as used in the US International Building Code (IBC. 2015) and the ASCE/SEI 43-05 Seismic Design Criteria for NPPs (US NRC, 2007) which could be a feasible approach for adaption is the hazard characterisation in a total context. However, a potential target spectra needs an end-to-end approach where interactions occur, and with significant uncertainties on defining the scenarios which can cause a certain ground motion to cause a damage state. More work would be needed before this is practical especially in the context of constraining the uncertainty of a long return period event in a low seismicity region such as Germany.

The resulting target spectra in a risk-targeted ground hazard definition represent ground motion for a given return period or equivalently, for a uniform hazard level. The conditional spectra approach allows to define realistic ground motion from the given target uniform hazard spectrum (for a given return period) for the purpose of probabilistic structural analysis (Lin et al. 2013). This methodology has been implemented in NARSIS for the selected site studies (Mülheim-Kärlich, Biblis and Trino Vercellese).

2.4 Full implementation of the MH Framework and key findings

The integration of hazard analyses and sites examined as part of D1.1 to D1.6, has been performed in an open-source and open-access software framework, so to be able to model and simulate single as well as multiple hazards (e.g. high winds or earthquake & high precipitations leading to structural damage and equipment flooding; or earthquake with fire-following or flooding-following due to damaged spent fuel pool or pipes, etc.).

Given the large amount of literature in this field, a key focus has been made on some more innovative and improved analyses for various topics, thus integrating D1.2-D1.5 together. As well as D1.1 to D1.6, the tools were there for successful independent hazard analysis of multiple hazards as shown in D1.7 (Daniell et al., 2021).



Earthquake (Mainshock Ground Motion)	No Interaction	Direct influence on aftershock GM
No Interaction	River Flooding through 5-day rainfall	No Interaction
Potential Foreshock influence on GM	No Interaction	Earthquake (Foreshock or Aftershock Ground Motion)

Figure 6: 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.

The first step before being able to move towards a risk-targeted hazard definition, needs an end-to-end approach where interactions occur, with significant uncertainties on defining the scenarios which can cause a certain hazard parameters to cause a damage state. More work is required in characterising this for any site. For any application of a MH framework, it should be adapted to the Operating Management Guidelines. So in NARSIS, a generic framework has been tested for use in a variety of settings with an extension of the state of the art in a few key fields.

The following concepts have been examined and require:

- The modelling of multiple hazards at locations which are realistic,
- Duration of the hazard type and of the operational aspects of dealing with individual hazards,
- Independent and dependent hazard types,
- Hazards, where there has been less analysis done previously,
- The modellability of the different hazards and their potential use,
- The use of the different modelling methods (mechanical, stochastic, empirical),
- The application to European conditions,
- When to undertake detailed site analysis.

Clear combinations such as Earthquake-Aftershock, Volcano-Dam, Earthquake-Flood as well as combinations of earthquake, flood, tornado and lightning were explored with the hazard curves for different examples being employed in the software. These hazard curves represent various perils including earthquakes, flood, hail, windstorm etc. as had been examined throughout the work package. These independent hazard combinations allowed for integration into other NARSIS work packages such as WP3 and WP4.

For dependent hazard types, as part of the scoping report in D1.6, identification of the threat of volcanic eruptions was identified for the NPP site of Mülheim-Kärlich. The Volcano-Low Water scenario was identified via the MH framework for dependent hazard types. As a single hazard, volcanic eruptions and the associated tephra output should impact the plant every 12,000 years. The probability of event damming on the River Rhine is set up using a model of low water, and tephra height to give a combined probability of damming. The event probabilities can then be calculated for the 9 event scenarios. A combined probability of 2.32×10^{-5} is seen for all scenarios to produce a dam sequence.

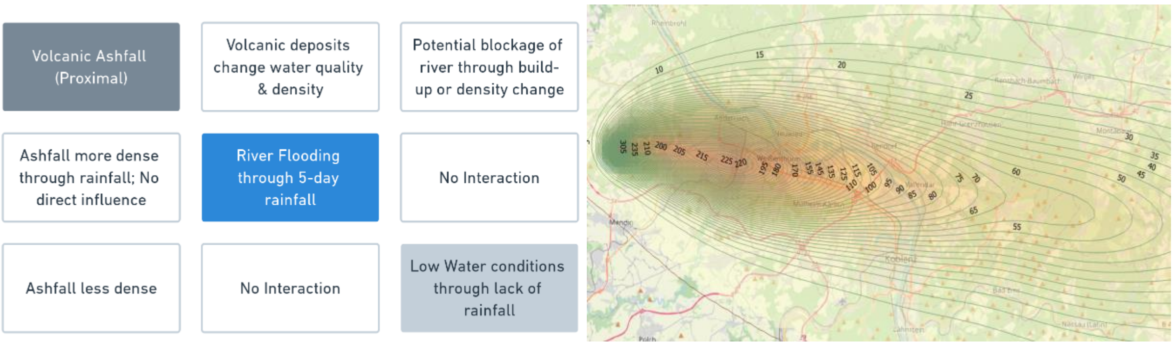


Figure 7: Volcano-Low Water interaction scenario: (left) interactions between volcanic ashfall and river flooding / low water conditions; (right) isopachs (n kPa) for one scenario of a Laacher See Eruption affecting the Mülheim-Kärlich site.

Such scenarios require detailed site modelling of the operational measures, however, the identification of such scenarios for decommissioned sites in WP1, shows the need for further research of MH scenarios, particularly on dependent hazards.

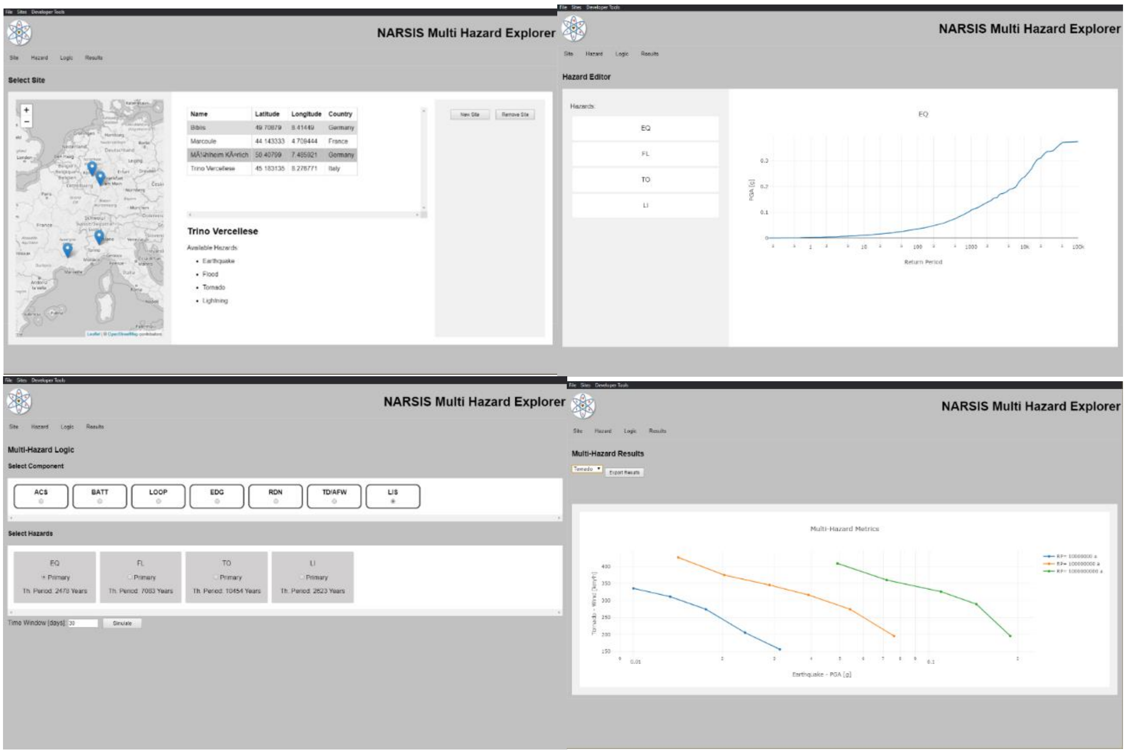
These scenarios thus require a combined process with uncertainty analysis, operational management plans and human processes using aspects of the following deliverables:

1) D2.8: Methods to incorporate human factors within a multi-hazard approach;
2) D3.3 Methodologies to constrain uncertainties in the components' modelling (causes and consequences;
3) D4.5 Reactor safety analysis results useful for Severe Accident analysis, considering deterministic and probabilistic approaches.

2.5 Software Solutions developed within NARSIS

The NARSIS Multi-Hazard Explorer (MHE) described in D1.8 (Schäfer et al., 2021) presented an entry-level tool to quickly review and assess multi-hazard scenarios. It was built on an open-source framework and can thus be extended with new features by any other developer. With its transparent data management and portable runtime structure, it can be used on almost any operating system, or could be even considered as a browser application in the future.

The software allows to view and manipulate hazard curves of which various samples are included to assess potential variations on the given sample data, e.g. w.r.t. the binning or shape. In addition, hazard curves can be combined for multi-hazard assessment and the consideration of secondary effects (like landslides or liquefaction). The user interface is built using the Electron framework in Javascript, allowing to have an open-source publishing without any external licensing costs, but also to deploy on Windows, Mac and Linux systems.



Name	Latitude	Longitude	Country
Biblis	49.70879	8.41449	Germany
Marcoule	44.143333	4.708444	France
MÃ¼hlheim KÃ¤rlich	50.40799	7.485921	Germany
Trino Vercellese	45.183135	8.278771	Italy

Trino Vercellese

Available Hazards:
- Earthquake
- Flood
- Tornado
- Lightning

EQ	FL	TO	LI
● Primary	○ Primary	○ Primary	○ Primary
Th. Period: 2478 Years	Th. Period: 7083 Years	Th. Period: 10454 Years	Th. Period: 2623 Years

Time Window [days]: 30 Simulate

Figure 8: NARSIS Multi Hazard Explorer screenshot – selection via SSC type

Fundamentally, the NARSIS MHE was developed to provide a straightforward way to assess the linear combinations of independent hazards. Multi-hazard is hereby defined as the linear combination of 2 independent hazards. The hazard with the higher occurrence frequency is defined as the primary hazard and any other one is called the secondary hazard. The tool uses given hazard return period curves of independent hazards, which are needed as input for the software, and computes occurrence probabilities for both hazards happening in the same time window. Combining more than 2 hazards is not part of the software but can be integrated by rerunning analyses. Similarly dependent hazards can also be applied currently externally and brought in as stochastic event set probabilities on one component of the linear combination. To understand and quantify the impact of MH scenarios, a clear working template and visualization tools have been set up (e.g. graphs of coinciding hazards for different return periods).

The NARSIS MHE is delivered in two different ways: it can be downloaded as pre-compiled runtimes (zip-archives) for different operating systems with no further installation needed, or the source-code can be downloaded or forked to be compiled by the user or for further development. Hereafter, we provide a link to the Github-repository: https://github.com/a-schaefer/NARSIS-MHE.

For future developments, we recommend to keep the open-software structure. Its generic nature allows the software to be used outside the nuclear field, but also provides a standalone which can be adapted by plant operators or modellers only for internal use on a specific site.

2.6 Recommendations for Regulators

The approach developed makes the multi-hazard assessment possible at the scale of a power plant. It should however be noticed that this approach is very plant specific, and although the methodology should screen all hazard types along the lines of the modified single hazards explored within ASAMPSA-E, and all the scenarios, there are still some combinations, which may be missed due to specific fragility loops, and/or dynamic hazard loops. In this way, the MH framework needs further calibration and is susceptible to be updated at completion of the NARSIS project.

The Level 0 (assessment of single hazards) is essential as it drives the quality and accuracy of the rest of the methodology. In this step, the uncertainty on input data has generally more consequences than uncertainty on the different hazard characterisation methods and models.

A research of available databases and catalogue across Europe, carried out in NARSIS WP1, showed that on national level, the availability of datasets strongly varies from country to country and also varies between the different natural hazards, highlighting a need of harmonization between European countries. On European and global level though, there are many datasets and catalogues as well as hazard maps available at lower resolution. The links of existing databases are going to be included in the NARSIS MHE open-source software in order to provide a state of the art in datasets.

The hazard characterisation methods are very different, using deterministic or probabilistic methods, in regards to the hazard type. The current methods applied for four natural hazards (earthquake, tsunami, flooding and extreme weather) are summarized in this report, as well as some improvement methods analysed in specific NARSIS deliverables.

Another important point regarding the hazard characterisation is the impact of non-stationarity of some extreme events. In particular, flooding and extreme weather hazards assessment have to take into account the effect of climate change, as well as the evolution of land use, and any other anthropogenic actions that may impact either the occurrence of hazard or its consequences.

The step from single to multi-hazard analysis involves the identification of secondary hazards and the consideration of possible interrelation between single hazards either in terms 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. It is thus possible to decide which multi-hazard scenarios are the most realistic.

The last steps of the integrated framework enable us to assess the modellability of the multi-hazard scenario and proceed to the numerical calculations of the occurrence probability of the given scenario and of its effects on the NPP components. In case of independent single natural hazards, the NARSIS MHE software can be used as well.

Uncertainty forms a major part of any result, given the large variability of events, the quantity and reliability of datasets (epistemic uncertainty) and simply the random nature of natural hazards (aleatory variability). Uncertainty quantification has to be taken into account at each step of the framework, from the hazard source to the site effects. An attempt is made to characterize this, where regression from historic information is undertaken.

It is also worth noticing that expert judgement and engineers specialists in many fields (seismologists, hydraulics, meteorological, statistics, etc.) are still necessary all along the process, from the hazard characterisation to the MH scenarios quantitative assessments.

Beyond the recommendations to regulators and the final workshop to be organised in February 2022, an EGU session in May 2020 as well as two training workshops were organised in September 2019 and April 2021. The EGU session aimed to share innovative approaches to developing multi-hazard risk assessments and their components, and to explore their applications to critical infrastructure management, disaster risk reduction and climate change adaptation. The session profiled a diverse range of multi-hazard risk and impact approaches, including hazard interactions, multi-vulnerability studies, and multi-hazard exposure characterization and approaches taken to assess multi-hazard risk to critical infrastructure. In covering the whole risk assessment chain, it was proposed that it will be easier to identify potential research gaps, synergies and opportunities for future collaborations as a result of an interdisciplinary session, which in itself gave healthy discussions as to operations after NPP events, as well as duration effects within hazards and the definition of “overlapping hazards”.

3 Fragility Assessment

3.1 Main objectives

The main objectives of the WP2 was to develop innovative methods to increase the reliability or reduce the uncertainties in the estimation of the responses of main NPP critical elements to external threats.

The approach taken was to develop and/or improve existing (deterministic/stochastic) models, in order to assess the impact of complex multiple external aggressions on the physical and functional integrity of main critical NPP system components, as defined in the WP4 reference plant.

These objectives were addressed within four main tasks and related main deliverables provided hereafter:

- Task 2.1: Inventories and definitions of the set of main critical elements for the NPP systems

  This resulted in deliverable D2.1.

- Task 2.2 – Improved models and methodologies for fragility assessment

  This task led to the following deliverables:

  - D2.2 & D2.10: theoretical aspects and applications related to the methodology to account for cumulative effects in the fragility assessment;
  - D2.3: seismic structural response of corroded RC components through experiments and simulations;
  - D2.4: Methodology to account for cumulative effects in the fragility assessment;
  - D2.5: Methodology to account for soil-structure interactions.

- Task 2.3 - Development of methods to derive vector-valued fragility functions in a multi-hazard approach

  This resulted in deliverables D2.7 (Derivation of hazard harmonized fragility models), D2.6 & D2.9 (Methodology to derive vector-based fragility functions I: theoretical aspects; II: applications).

- Task 2.4 - Development of methods to incorporate human factors within a multi-hazard approach

  This resulted in deliverable D2.8.

3.2 Identifying critical components in NPP systems

The regulation with U.S. Nuclear Regulatory Commission 10 CFR 50.69 (NRC, 2004) introduced risk-informed categorization and treatment of structures, systems and components (SSC) for nuclear power reactors. The safety significance of SSCs is determined by an integrated decision-making process, incorporating risk and traditional engineering insights. Based on their significance the SSC's are classified in four Risk-Informed Safety Class (RISC), given on Figure 9 (a). The RISC-1 and RISC-2 are considered as safety significant classes while RISC-3 and RISC-4 are low safety significant (LSS) classes. In NEI 00-04 (NEI, 2005) the nuclear industry developed a categorization process that utilizes a series of evaluations to determine the proper risk-informed safety classification for SSCs as shown in Figure 9 (b). The NEI 00-04 uses term "high-safety-significant (HSS)" to refer to SSCs that perform safety-significant functions. The NRC understands HSS to have the same meaning as "safety-significant".

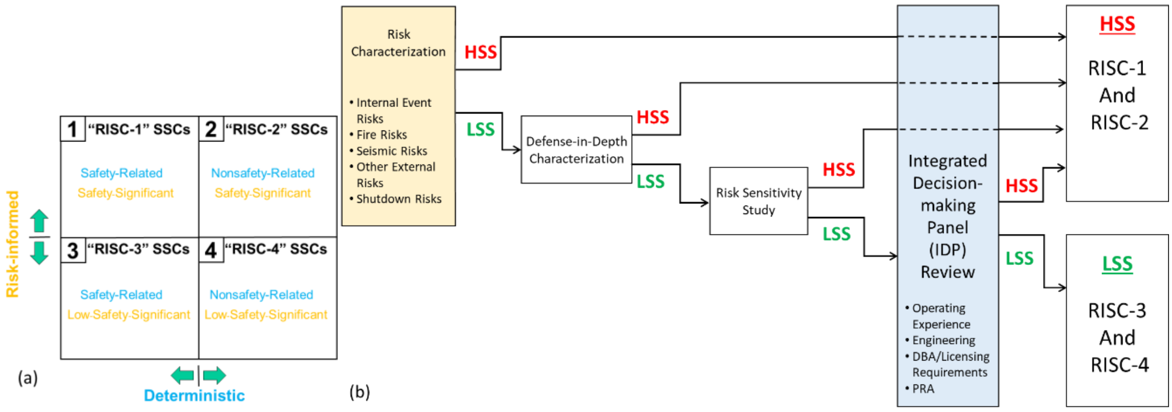


Figure 9: (a) §50.69 RISC Categories (adapted from Figure 1 of (NRC, 2004)) and (b) Summary of NEI 00-04 Categorization Process (adapted from Figure 1-2 of (NEI, 2005).

The event tree and the fault tree are two basic methods used in the PSA. The fault tree analysis is based on Boolean algebraic and probabilistic basis that relates probability calculations to Boolean logic functions. The logical gates integrate the primary events to the top event representing the undesired state of the system. The primary events are the events, which are not further developed, e.g. the basic events. The basic events are the ultimate parts of the fault tree, which represent the undesired events, e.g. the component or system failures.

Determination of the safety significance is based on a risk-informed approach with the utilization of quantitative importance measures. The first group consists of the measure that is called Fussell-Vesely (FV) Importance. The second group of the importance measures depicts the change of the system unavailability when the contributor's failure probability is set to 0 or 1. These importance measures are named Risk Achievement Worth (RAW), also named as Risk Increase Factor (RIF), and Risk Reduction Worth (RRW), also named as Risk Decrease Factor (RDF).

The PSA importance measure criteria used to identify candidate safety significant SSC's are:

- Sum of FV for all basic events modeling the SSC of interest, including common cause failure (CCF) > 0.005
- Maximum of component basic event RAW > 2
- Maximum of applicable common cause basic events RAW > 20.

If any of these criteria are exceeded, it is considered candidate safety significant SSCs.

The results of **both case studies** were post-processed in order to rank them according to their relative importance. In one case, a seismic Level 1 PSA was performed. In the other case, a seismic margin assessment (SMA) was performed, for two different site classes (one rock site and one soil site). The SMA was conducted according to the PSA-based approach.

Based on these case studies, the following SSCs are identified as 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 present report;
- Distributed systems (HVAC, piping, cable raceways).

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

- primary circuit depressurization (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.

3.3 Accounting for cumulative effects in fragility assessment

A preliminary evaluation of the reliability of Gen III NPP components relevant for safety subjected to earthquake events and ageing was performed.

To account for the impact of cumulative effects by succession of events and ageing mechanisms in seismic fragility assessment of SSCs, a deterministic approach was adopted and several thermos-mechanical and seismic simulations were performed by means of finite element (FE) codes on the NARSIS generic NPP, used as reference for this assessment.

Regarding ageing mechanisms, structural degradations due to accelerated flow corrosion, creep and time and/or temperature material properties degradation, are among the key factors assessed to obtain a realistic evaluation of the class-1 safety structure (specifically reactor buildings and primary pipe), especially when extreme environmental demands, such as large earthquakes are considered.

Since the performance of all plant components may be affected by ageing, there is a need to evaluate the effect that aged components have on system performance and plant safety. After the identification of the critical SSCs from the plant operation and safety point of view, we identified the operational loadings, stressors, and ageing mechanisms depending on the components' constitutive materials. Then, a methodology for performance prediction was set and FE simulations performed to assess the ageing effects and consequences on the integrity of the structure or identifying the design improvement actions.

Figure 10 shows the 3D FE plant model implemented for ageing analysis. The seismic evaluation was performed considering 50 different ATH records.

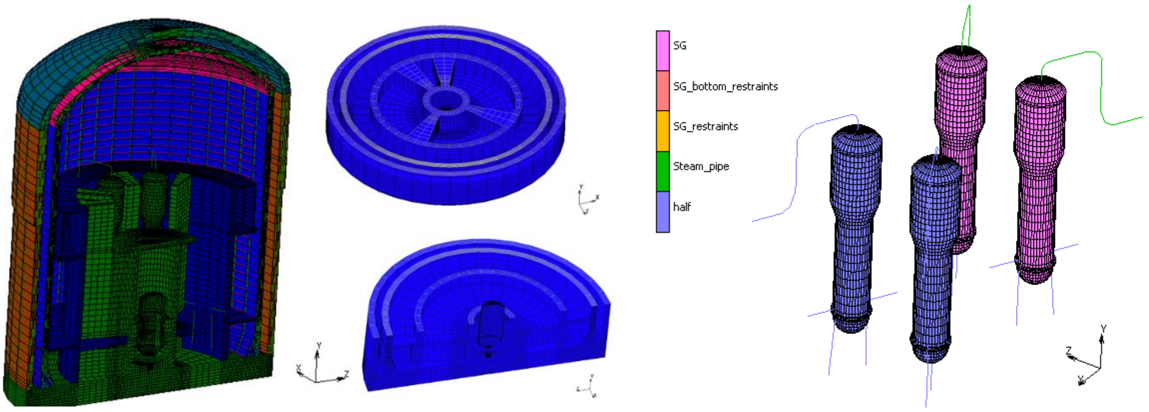


Figure 10: Overview of the FE model of the containment system (right) and steam generators with pipe (left)

Thermo-mechanical FE analyses were also performed on the primary pipe (straight and bent parts), considering operating conditions and subjected to homogeneous as well as heterogeneous (either generalized or localised) wall thinning, assumed to represent ageing mechanisms.

Results from the several FE analyses confirmed that ageing of structural elements is likely to degrade the mechanical performance and impair the structural capacity and reduce the residual safety margin. Results seem to confirm the overall reactor containment reliability even though buckling could affect some internal components. The FE approach is suitable to account for cumulative effects by succession of events and ageing mechanisms as it allows for deriving the residual capacity as well as the residual life of SSCs.

3.4 Accounting for Soil-Structure Interactions in fragility assessment

The purpose here was to document employed methodology and to provide a probabilistic analysis of the Nuclear Island (NI) structures incorporating Soil-Structure Interactions (SSI) effects. The final expected results were local seismic demands to be used as input for SSC fragility analysis.

In fact, a key element of the Design extension Seismic Capacities (DESC) is to obtain seismic structural response, including SSI effects, and gain generic insights into performance and potential vulnerabilities of SSC when subjected to the beyond design seismic event. In addition, these insights may be used to bring correction to the design concepts.

Two cases of SSI effects were considered in this work:

1) A surface founded structure, where the ground surface and structure foundation plate were at the same elevation of 0.00 m;
2) An embedded structure, where the top surface was at elevation of +10.00 m and the foundation plate, at 0.00 m. Additionally, an effective embedment was considered for this case following the section DA 3210 of RCC-CW.

The NI FE model was converted from ANSYS code format to the ones required for SC-SASSI and Cast3M FE codes used here for analyses. The conversion was verified by benchmarking SC-SASSI, Cast3M and ANSYS FE models, leading to a good agreement of in-structure response spectra (ISRS) for a same excitation and fixed base boundary conditions.

Then, the soil and structural properties were randomized to obtain the probabilistic SSI models. Two random variables were introduced using Latin Hypercube Sampling (LHS) to characterize the variability in the dynamic soil properties, i.e. shear wave velocity (V_S) and damping ratio associated with shear wave. The Poisson's ratio for each of the randomized soil profiles were assumed constant. Similarly, LHS factors were applied to generate randomized structural properties (stiffness and damping ratio). 19 SSI models were developed by pairing the soil profiles with corresponding structural models. The approach for performing the probabilistic analysis is shown in Figure 11.

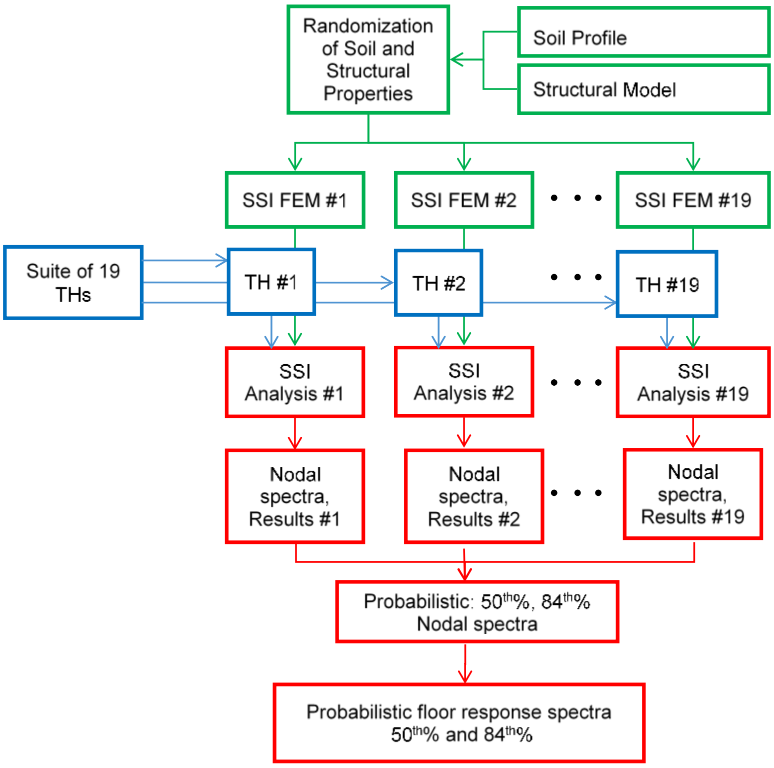


Figure 11: Probabilistic SSI analysis approach

Probabilistic SSI involves running variations of a SSI model through a suite of time histories, where each model variation is uniquely paired to one time history. The SSI analyses in SC-SASSI include the Abrahamson soil plain-wave coherency model to consider the effects of ground motion incoherency.

Finally, the seismic responses from the analyses for both SSI cases were extracted at predefined key locations of the Reactor Building Containment, Reactor Building Internal Structures, and Safeguard Buildings.
The probabilistic responses at each location was evaluated and the envelop of maximum responses at each rigid and flexible location was performed to generate the Probabilistic Floor Response Spectra (PFRS), which were calculated for 50% and 84% non-exceedance probabilities (NEP). A benchmarking of these PFRS results between SC-SASSI and Cast3M was also performed. Despite the differences found, the comparison of PFRS were deemed acceptable. Hence, they may be used in subsequent seismic fragility evaluations of the SSCs.

3.5 Deriving vector-valued fragility functions

3.5.1 Introduction

A fragility function is a mathematical tool that expresses the probability of reaching or exceeding a damage state DS given the level of external loading, represented by an intensity measure IM. In the case of complex hazard loadings (e.g., earthquake waveform), a single scalar IM may not be sufficient to represent the severity of the aggression. As a result, conventional fragility curves using scalar IMs may come with a larger dispersion (i.e., uncertainty) in order to represent the imperfect relation between the IM and the loading actually applied. Such uncertainty then propagates through the PSA chain, potentially leading to unnecessary reliability margins.

Therefore, one of the purposes of this activity is to investigate the benefit of using multiple IMs (referred to as vector-valued IMs) in the formulation of fragility functions. Such a concept is especially suited to the case of seismic fragility assessment, where a strong-motion record may be represented by a wide range of parameters such as peak amplitude, frequency content or duration (Seyedi et al., 2010; Gehl et al., 2013).

A fragility model using vector-valued IMs is also introduced in the case of multiple hazard events: in this case, each IM represents the loading level of a different hazard and the consideration of all IMs provides the means to quantify the probability of damage for multi-hazard scenarios. Such an approach relies on the combination of failure modes due to single hazard loadings and on the assessment of cumulative hazard effects on the studied system (Gehl & D’Ayala, 2016).

3.5.2 Methodological developments

In the case of seismic loading, the approximation of a complete waveform (i.e., acceleration time history) by a single IM leads to an aleatory type of uncertainty, sometimes referred to as “record-to-record variability” (i.e., two different waveforms may have the same IM but results in very different structural responses). Therefore, the selection of the most adequate IM for the derivation of fragility functions should obey a set of criteria, such as: *(i) efficiency*, the ability of an IM to induce a low dispersion in the distribution of the structural response; *(ii) sufficiency*, the ability of an IM to “carry” the characteristics of the earthquake that has generated the ground motion; *(iii) computability*, the ability to quantify the IM accurately with current ground-motion models.

In the NARSIS framework, a list of computable IMs was pre-selected and evaluated through a *proficiency* indicator (Padgett et al., 2008), which combines *practicality* and *efficiency* criteria. This procedure was applied to two case studies:

1. The main steam line of a PWR (Rahni et al., 2017; Gehl et al., 2019);
2. A reactor building containing a steam generator and a piping system.

In the first application, it was found that a combination of two IMs, namely the PGA and the spectral acceleration (SA) at a given period *T*, provides a higher proficiency indicator than when considering the single IMs separately. This is confirmed by deriving the corresponding vector-valued fragility function (i.e., fragility surface) and by comparing it to the single-IM fragility curve (see Figure 12). Taking advantage of the PGA-SA(*T*) distribution of the data points, “slices” of the fragility surface were extracted for various percentile values and were plotted as a function of SA(*T*) only.

It is possible to make an analogy with the double-lognormal fragility model introduced by Kennedy et al. (1980), which separates aleatory and epistemic types of uncertainty. An interpretation of the graphical construction in Figure 12 leads to an estimation of the part of the variance that is transferred from the aleatory component (i.e., record-to-record variability) to the epistemic component when using a vector-valued fragility function: in the present example, it was found that around 20% of the total variance may be reduced by introducing the combination of two IMs.

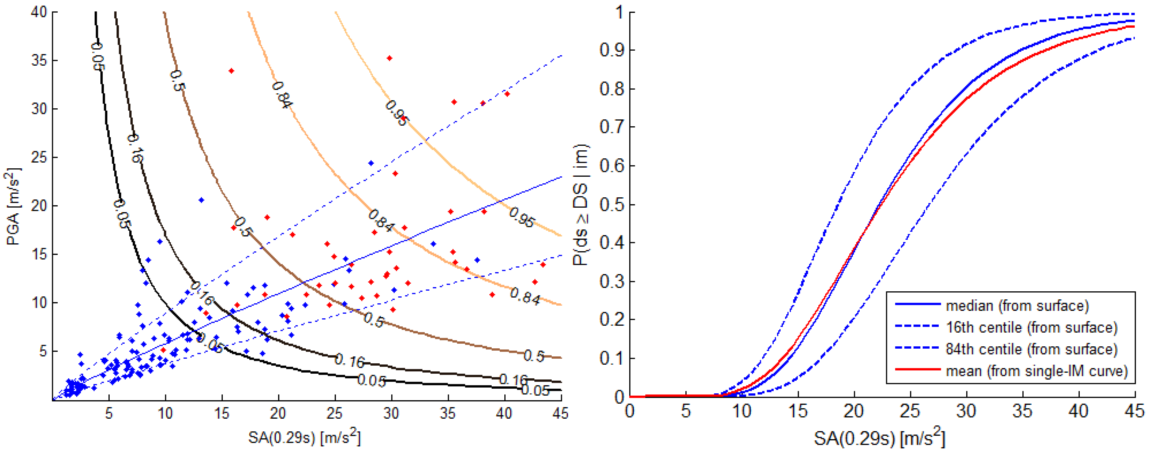


Figure 12: Left: fragility surface w.r.t. PGA and SA(T=0.29s), the solid blue line represents the median of the PGA-SA(T=0.29s) distribution and the dashed blue lines the 16%-84% confidence intervals; Right: Equivalent fragility curves w.r.t. SA(T=0.29s).

Regarding multiple hazards, two cases were considered:

- When multiple loadings are applied simultaneously, joint probability distribution functions should be considered for the fragility function construction coming from the combination of hazard loadings. In this case, a multivariate Generalized Linear Model regression may be applied to represent the contribution of each hazard loading. Another option lies in the identification of hazard-specific failure modes and the assembly of hazard-harmonized functionality states, through system reliability tools (Kang et al., 2012) or Bayesian Networks (Gehl & Rohmer, 2018).
- When a first hazard loading may degrade the resistance of the SSC or alter the conditions for when a subsequent hazard loading is applied (i.e., sequence of events), damage-state-dependent fragility functions should be considered. The hazards may be correlated (i.e., same source event, or one hazard event triggering another) or independent (i.e., occurrence within the same time window). In the case of numerical simulations, models that account for the deterioration of materials or components (see Section 3) are required in order to update the fragility w.r.t. hazard H_2, given the damage induced by hazard H_1.

An example of multi-hazard fragility function was developed for a flood protection levee: the model considers a succession of hazard events, namely a volcanic eruption (deposit of tephra loads on the levee) followed by an earthquake (mainshock and aftershock). Some results are presented in Figure 13, where DS_1 represents minor damage and DS_2 extensive damage.

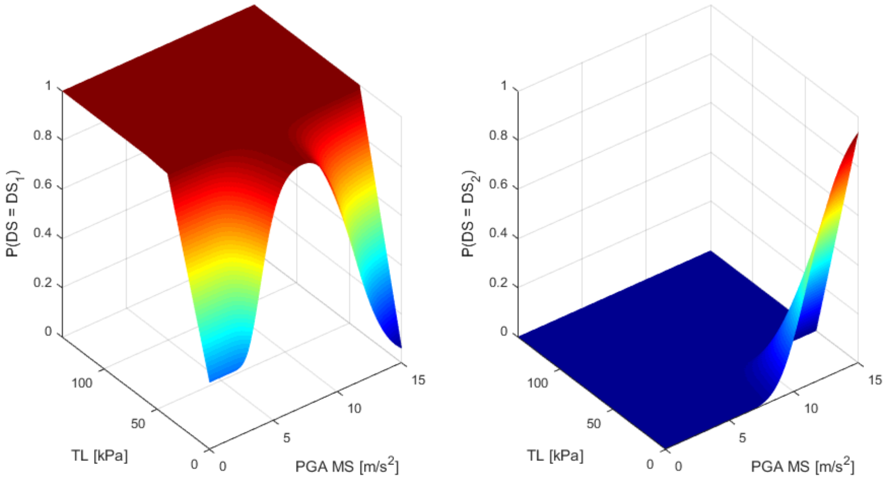


Figure 13: Probability of the levee being in states DS1 (Left) and DS2 (Right) with respect to mainshock PGA (PGA MS) and tephra load (TL), with aftershock PGA = 3.64 m/s2.

3.5.3 Main contributions and findings

The developments carried out on vector-valued fragility functions for seismic loading have led to the following observations:

- 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.

It has also been shown that multiple intensity measures and physical failure modes can be combined in order to generate fragility models for a wide range of multi-hazard configurations. Provided that the required hazard-specific physical models are available, the following statistical tools are able to cover most of the multi-hazard cases:

- Multivariate GLM regression or MLE are to be used for the estimation of fragility parameters given a set of conditioning variables.
- Algorithms and procedures based on the system reliability theory (e.g., Kang et al., 2012) are able to combine hazard-specific failure modes in order to model the SSC functionality states of a given SSC. Either joint probabilistic of failure or damage-state-dependent fragility functions may be derived from this framework.

4 The Multi-risk integration framework for safety analysis

4.1 Main objectives

One of the key objectives pursued within the NARSIS WP3 has been to improve the integration of external hazards and their consequences with existing state-of-the-art risk assessment methodologies in the industry.

The approach taken was to investigate, further develop and apply the Bayesian Networks (BN) and the Extended Best Estimate Plus Uncertainty (E-BEPU) approaches, and to compare their capabilities w.r.t. safety assessment of NPP.

Another key objective was to develop tools/methods adapted to NARSIS in order to identify the most influential sources of uncertainty and to prioritise those which should be reduced accordingly. The expected result was that uncertainty on modelling results can ultimately be constrained before integration.

These objectives were addressed within four main tasks and related main deliverables provided hereafter:

- Task 3.1: Review and comparison of risk integration methods from high risk industries

  This resulted in deliverable D3.1 (Mohan et al., 2018).

- Task 3.2: Building and integrating a BN

  This task led to the following deliverables:

  - D3.2 (Mohan et al., 2021): development of risk sub-networks;
  - D3.3 (Rohmer & Gehl, 2020a): constraining the uncertainties in the components' modelling (causes and consequences);
  - D3.4 (Mohan & Vardon, 2020a): sub-networks integration.

- Task 3.3: Improvement of flexible approaches and procedures relying on expert-based information

  This resulted in D3.7 (Rohmer et al., 2020) and D3.11 (Prošek & Volkanovski, 2021), in which an analysis of uncertainties by identifying, classifying and analysing the main sources of uncertainties in a specific scenario, was carried out.

- Task 3.4: Combining probabilistic and deterministic approaches in E-BEPU analyses

  This task led to the following deliverables:

  - D3.8 (first part of Dusic et al., 2019): development and description of E-BEPU method;
  - D3.9 (second part of Dusic et al., 2019): use of E-BEPU for evaluation of Defence-in-Depth (D-i-D);
  - D3.10 (Dusic and Hortal, 2020): use of E-BEPU for Design Extension Conditions (DEC).

4.2 The Bayesian Networks integration approach

4.2.1 General overview

Based on the review of various risk integration methods performed in the deliverable D3.1 (Mohan et al., 2018), Bayesian networks (BNs) have been identified as a suitable framework for considering external hazards and consequences and has been investigated and developed further during the NARSIS project.

A specific case study was developed in order to study the use of BNs in NPP risk assessment. This was an accident scenario at the virtual power plant presented in D4.1 (Bruneliere et al., 2018), with loss of offsite power (LOOP) as the initiating event, under the following conditions:

- LOOP has occurred following one or more external hazard events.

- During the LOOP situation for an extended time, at least one emergency diesel generator is needed; therefore, all four Emergency Diesel Generators (EDG) failures would lead to a partial station blackout (SBO) situation. In addition, total SBO will happen if two additional Diesel Generators known as Ultimate Diesel Generators fail.
- If partial blackout occurred, Secondary Cooldown (SCD) system is actuated. SCD needs to assure that at least one out of four Steam Generators (SG) will be used for residual heat removal (RHR) or partial cool down (PCD).

BNs were developed for technical aspects as well as human and organisational aspects associated with the above accident scenario, while exploring various research aspects, following the flow chart presented in Figure 14. These BNs (subnetworks) were used to compare the approach to existing methods in probabilistic safety assessment (PSA). An overall risk integration methodology was presented to integrate the various technical and human BNs, while including their interactions with external hazards.

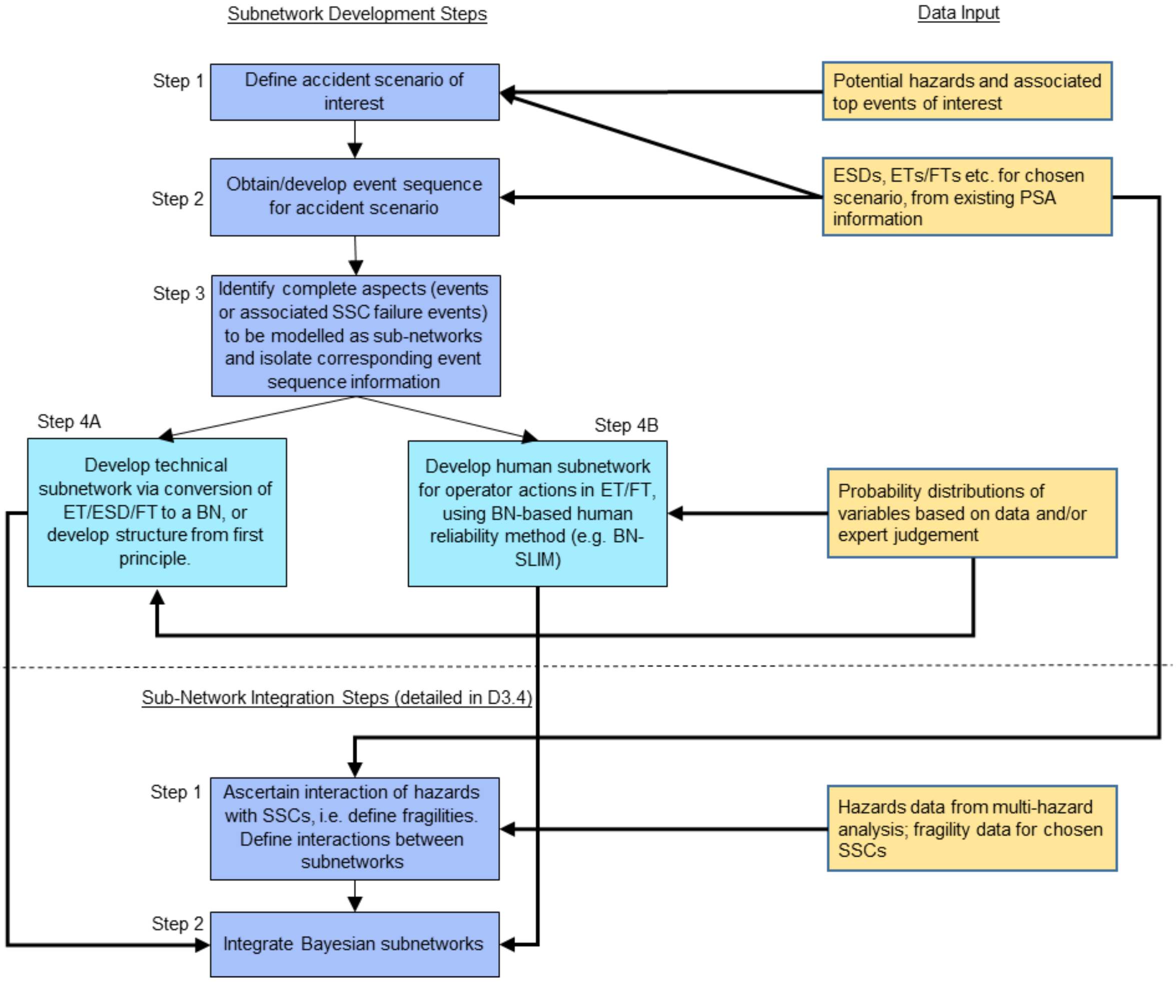


Figure 14. Generic methodology for development of Bayesian subnetworks for external hazard related NPP accident event (Mohan et al., 2021).

4.2.2 Comparison with other PSA approaches

The above mentioned SBO accident scenario was used to compare BNs with fault tree analyses that are currently widely used in PSA. The methods were compared under various risk assessment aspects such as top event probability estimation, failure diagnostics, importance measures, the incorporation of multi-state variables and statistical dependencies. A new approach to common cause failure (CCF) modelling in BNs, using correlations, was presented and compared with the Multiple Greek Letter (MGL) model that is often used in PSA (in D3.4, Mohan and Vardon, 2022).

4.2.3 Technical BNs

The event and fault trees associated with the chosen accident scenario were obtained from D4.1 (Bruneliere et al., 2018) and are summarised in Table 2. These event and fault trees, for the SBO and SCD failure conditions, were converted to BNs as technical subnetworks presented in D3.2 (Mohan et al., 2021). Technical subnetworks were also developed for the inclusion of vector-based fragility (Gehl and Rohmer, 2018) and the geotechnical modelling of flood control dikes (Mohan et al., 2019).

Table 2: Technical BNs exploring various research aspects (Mohan et al., 2021)

Subnetwork Reference	Subnetwork Content	Research aspect(s) explored
SBO BN	Represents fault tree for SBO under LOOP	• Comparison of fault trees and BNs with respect to: (i) Top event probability (ii) Failure diagnostics (iii) Importance measures (iv) Multi-state variables (v) Statistical dependencies
SCD_11 BN	Represents fault tree for SCD failure given SBO	
Flood defence BN	Geotechnical reliability of a flood control dike	• Using the BN as a surrogate model for computationally intensive numerical analyses • Uncertainty representation and propagation • Reliability updating based on testing • Use of continuous probability distributions and dynamic discretisation
Fragility BN	Model interaction of hazards and fragilities	• Hazard-fragility interaction using BNs • Multiple hazard intensity measures and vector-based fragility

4.2.4 Human and organisational aspects

A human BN was developed to estimate human error probability (HEP) for an operator action during event progression from SBO to SCD within the accident scenario (D3.2, chapter 7 (Mohan et al., 2021)). A new BN-SLIM approach was implemented for HEP estimation and compared to the existing BN-SPARH method (Abrishami et al., 2020). The probabilities of performance shaping factors (PSFs) and their influence on the operator's failure to gather information (I), make decisions (D) and take actions (A) were obtained via structured expert judgement elicitation (Figure 15).

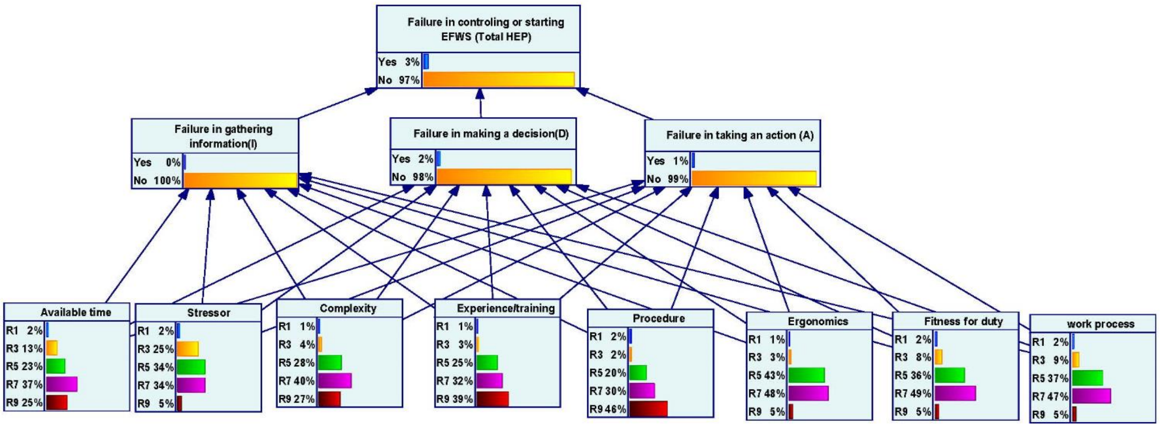


Figure 15. BN-SLIM with the probabilistic evaluation of performance shaping factors, in HEP estimation (Mohan et al., 2021)

4.2.5 Risk integration

The technical and human BNs were integrated along with external hazards using an overall risk integration framework (D3.4, Mohan and Vardon, 2022). External hazard events were selected based on a decommissioned plant at Mülheim-Kärlich, Germany as detailed in D1.6 (Daniel et al., 2019). The framework involves a step-wise, iterative multi-hazard risk methodology using BNs to arrive at an efficient BN model for the given risk problem (Mohan and Vardon, 2022). With every iteration the BN is trimmed down by removing inconsequential variables (or ranges within their probability distributions) and dependencies. The integrated risk BN can be used to assess the impact of individual subnetworks, their constituent variables and their interdependencies, on the overall risk estimate.

4.2.6 Main contributions and findings

Based on the demonstrations and findings of this task, BNs can be developed for various reliability and risk estimation applications in multi-hazard PSA. Developments were made in various aspects:

- 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, especially in asymmetric systems. The method can also simplify visualisation of BNs for complex systems with many redundancies.
- 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 HEP, was shown to compare favourably with existing methods. The approach was coupled with structured expert judgement elicitation to populate the probabilities within the BN, highlighting its applicability in data-scarce NPP risk problems.
- A step-wise, iterative framework for multi-hazard risk integration, using BNs, was presented. Using this framework, the aforementioned technical and human BNs, with their respective developments and features, were integrated under a single BN-based risk model.

4.3 Constraining uncertainties

4.3.1 Introduction

Many NARSIS WPs involve complex models for respectively characterizing the physical external threats and the vulnerability and integrity assessment of NPP system components. In practice, this imposes processing a large number of sources of uncertainty regarding parameter uncertainty, but also model uncertainty. As a representative example, the finite-element model of an anchored steam line and of a supporting structure under seismic solicitations (as investigated by Gehl et al., 2019) implies accounting for several tens of different sources of parametric uncertainties (not to mention uncertainties related to the model set-up). Building upon the best practices for uncertainty assessment (de Rocquigny et al. 2008), special attention has been paid to characterise uncertainty pervading NARSIS models by dealing with three NARSIS specificities:

(1) The use of Bayesian Networks (BNs);
(2) The question of components' fragility;
(3) The use of expert-based information.

4.3.2 Constraining uncertainty in BN modelling

A comprehensive review of the main sources of uncertainty has been performed (Rohmer, 2020). On this basis, uncertainties related to the parameters of the Conditional Probability Model have been identified as a key aspect and are addressed in D3.3 (Rohmer & Gehl, 2020a).

To deal with this problem, the most widely used approach is based on sensitivity functions for discrete BNs, and on partial derivatives for continuous BNs. Yet, these approaches only provide information on the local influence, and the exploration of the sensitivity remains limited. To overcome this limitation, a new approach named “Boosted Beta Regression” (Rohmer & Gehl, 2020b) has been developed. The approach has the advantage of being generic (it can be applied to any kind of BN, i.e. discrete, Gaussian or hybrid), and robust to the number of parameters (that can rapidly increase, typically reaching several dozens, even for moderate number of BN nodes). Performance assessment of this new tool has been done using two real cases (i) for assessing the damage of reinforced concrete structures; (ii) for studying the problem of station blackout (Figure 16(a)) following an earthquake at a given NPP sub-system (Gehl & Rohmer, 2018). An example of sensitivity analysis result is provided in Figure 16 (b). This shows how perturbing the value of the fragility curve (EDG1) impacts the probability of occurrence of on-site power loss Pr(SYS) leading to a situation of “quasi-systematic” system failure when EDG1 is varied by +50%.

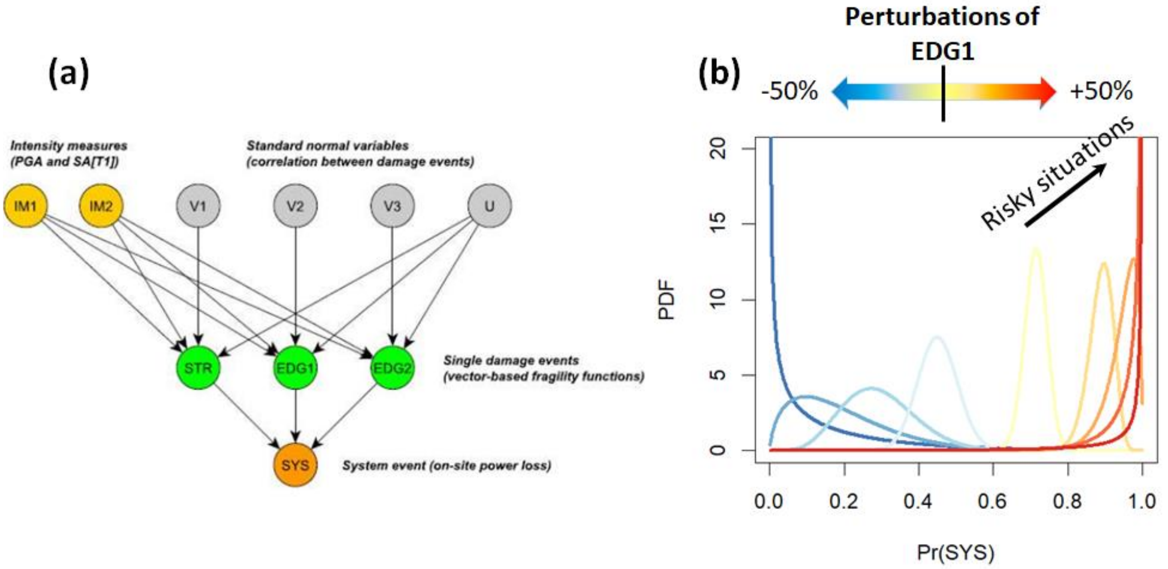


Figure 16. (a) Structure of the BN used to model the probability of occurrence of on-site power loss (denoted Pr(SYS)) with respect to 2 earthquake intensity measures (Gehl & Rohmer, 2018); (b) Influence of the fragility curve (EDG1) on Pr(SYS).

Finally, to further support WP3 BN developments, a procedure described in D3.11, has been proposed to identify, classify and analyse the main sources of uncertainties that affect the progression and consequences for the critical event of Station Blackout (Prošek and Volkanovski, 2019, 2021). The identification of the most important sources of uncertainties of the parameters was done on basis of results of the previous parametric studies and sensitivity study of deterministic calculations with the fast Fourier transform based method by signal mirroring (FFTBM). The analysis of the uncertainties of the selected parameters shows that both external (i.e. operator actions) and internal parameters (related to reactor coolant system of the NPP) may be source of large uncertainties. Figure 17 shows, based on the findings of the analysis of plant response (visual observation of calculated scenarios), the key progression of the SBO event scenario with the main events and operator actions which can be included in risk analysis tools.

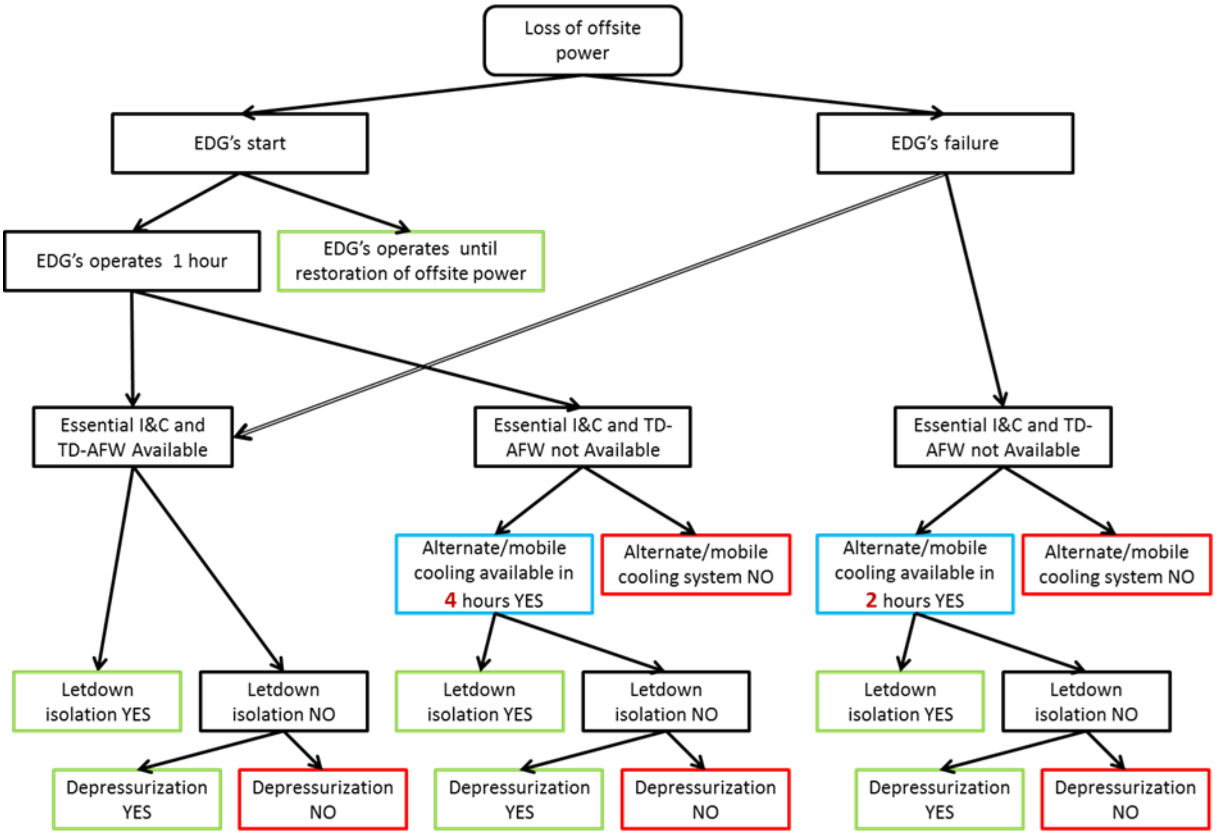


Figure 17. SBO event progression tree (Prošek and Volkanovski, 2019)

4.3.3 Constraining uncertainty in fragility assessment

A Bayesian updating framework has been proposed, by combining an Artificial Neural Network, an adaptive training algorithm and an amplification-factor-based construction of the likelihood function (Wang et al., 2018; Rohmer & Gehl, 2020a). The framework allows for an improved seismic capacity estimation and possible reduced uncertainties based on information from experience feedback.

Applying to the KARISMA (KAshiwazaki-Kariwa Research Initiative for Seismic Margin Assessment) benchmark and using damage data collected from the field observations and the database of the Seismic Qualification Utility Group (SQUG), results show that the proposed tool allows to reduce epistemic uncertainties, i.e. related to the lack of knowledge (also named the reducible part of uncertainty) in the fragility curves as the ones used in NARSIS.

4.3.4 Constraining uncertainty in expert-based information

The feasibility of new approaches / procedures taking advantages of new uncertainty theories (that generalises the use of classical probabilities, see e.g., Dubois & Guyonnet, 2011) have extensively been explored either for (i) the modelling of expert knowledge and reproducing expert-like reasoning based on fuzzy expert systems (D3.7: chapter 5 (Rohmer et al., 2020)) or (ii) the evaluation of expert-based information to complement the classical model of Cooke (D3.7: chapter 5 (Rohmer et al., 2020), and Rohmer & Chojnacki, 2021). Considering the latter aspect, using an extensive out-of-sample validation procedure, two aspects were investigated using 33 expert datasets: (i) robustness to the set of calibration questions used to estimate the scores, i.e. whether the best and worst performing expert differs; (ii) forecast performance, i.e. the degree of accuracy and informativeness of the derived forecast intervals. An interactive web app to showcase these developments is publicity available here: https://github.com/rohmerj/ExpertScoring.

4.3.5 Main contributions and findings

With the new developments for uncertainty characterisation, any practitioner of NARSIS is equipped with efficient sensitivity analysis tools to identify most influential sources of uncertainty and to set up prioritisation for reducing them. These developments, though dedicated to the specific aspects addressed within NARSIS, are of interest for any practitioners that are confronted with uncertainty analysis in safety assessments as shown by our applications to multiple and diverse real cases.

The application of the methods to the SBO event showed how these methods could constrain uncertainties and identify input into BNs. In case of modelling of operator/human actions, the human failure probability for these actions can also be assessed and included.

Finally, a particular result is for the treatment of expert-based information using the tools of new uncertainty theories. These have been identified as valuable ingredients to support the safety analysis, and for NARSIS project in particular. They should however not be seen as supplements to “classical” probabilistic tools, but rather as complements to nuance the results using expert-based information, to put light on different perspectives, and to highlight potential flaws in the assessment process. 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 the decision-making.

4.4 The E-BEPU methodology

4.4.1 Introduction

Safety analysis of nuclear power plants and other nuclear facilities has been historically developed at two levels. In the first level the objective is to ensure that the plant design verifies the safety design specifications, with the focus on safety systems which provide protection and/or mitigation against abnormal occurrences in different operational states. In the second level, the objective is to estimate the potential for plant states that exceed the design provisions and may result in consequences beyond the design limits. Typically, the first level analysis has been based on deterministic methodologies while the second level has relied on the use of probabilistic methodologies.

For some time, practitioners of safety analyses for nuclear power plants have been making efforts to combine deterministic and probabilistic safety analysis methods in order to achieve coherent methodologies that would take the advantages of both approaches when assessing any aspect of the safety of nuclear installations. In many cases these efforts resulted in essentially deterministic safety analysis (DSA) taking insights/results from the probabilistic safety analysis (PSA) where needed or vice versa.

4.4.2 Methodological developments

E-BEPU is a safety analysis methodology applicable to the analysis of Postulated Initiating Events (PIE) in complex facilities and, in particular, in nuclear power plants. Deterministic methods have been usually applied for plant safety verification. For this reason, licensing safety analyses are often referred to as Deterministic Safety Analysis (DSA). However, different approaches have been used and accepted by regulators. Best-Estimate Plus Uncertainty (BEPU) methodologies are now widely accepted for the analysis of Design Basis Accidents (DBA). In this type of methodologies, simulation of the plant dynamics is based on best-estimate models. Uncertainties are considered in initial and boundary conditions, in properties of the system and in physical models. E-BEPU is an extension of the BEPU methodologies with two important improvements. On the one hand, it incorporates uncertainty in the configuration of the safety systems involved in PIE initiated accidents. On the other, it requires compliance with additional acceptance criteria with an increased tolerance level in order to avoid possible cliff-edge effects. Both features contribute to a better implementation of Defense-in-Depth principles.

Within deliverable D3.8 (Dusic et al., 2019), a detailed E-BEPU methodology has been fully developed and described with all the advantages that it brings. The practical application of this methodology has been demonstrated within the deliverable D4.5 in WP4, where the application of E-BEPU has been demonstrated on the NARSIS standard design (generic) plant model, the work being done by the NARSIS colleagues from WUT, Poland in close cooperation with NUCCCON GmbH.

Application of E-BEPU for evaluation of defence-in-depth (DiD) has been demonstrated within the deliverable D3.9 (Dusic et al., 2019). In cases when E-BEPU discovers deficiencies in design, there is a need for its revision. Such deficiencies point to the need of increasing the success probability of the sequences associated to the particular PIE. This can be achieved by:

i. Enhancing the performance of safety systems (protection performance). In many cases, lack of performance could be due to inadequate initiation set-points. In other cases, a better performance can be achieved by increasing the capacity of some system components, e.g., an injection pump.

ii. Enhancing the reliability of the safety systems (protection reliability). This way, sequences with protection failures could have a lower probability and become candidates for reclassification or elimination.

iii. Adding a new level of protection. That is, introducing a new safety system with its corresponding header in the dynamic event tree. This results in additional branching points in failed sequences. Examples could be an alternative rod insertion system, a dedicated diesel generator, etc. This way, sequences including the new protection would likely become compliant with the acceptance criteria while sequences where the new system is also failed would be of lower probability. Both effects would contribute to the acceptability of the PIE analysis results.

The use of E-BEPU methodology for evaluation of Design Extension Conditions (DEC) has been fully described in deliverable D3.10 (Dusic and Hortal, 2020). The main difference between DBA and DEC is that for DBA, we rely on safety systems, whereas in DEC, safety features are required. Regulatory requirements for safety systems are much stricter and their enforcement quite uniform among different countries. E-BEPU methodology provides an elegant way to implement the graded approach to safety analysis defined in the IAEA-SSR-2/1 Rev 1 by treating DEC as the next higher class after the highest DBA class.

The use of E-BEPU methodology for Severe Accident Management Guidelines (SAMGs) has been demonstrated in deliverable D5.5 of WP5. Although the verification of the design of safety features for DEC provided in SAMGs is always a difficult task, E-BEPU provides additional insights that can be used for the development and validation and verification of SAMGs, especially by identifying possible cliff-edge effects on one hand, and by identifying very unlikely event sequences that can be treated as “practically eliminated” on the other hand.

4.4.3 Main contributions and findings

Within the NARSIS project, a detailed E-BEPU methodology has been developed and demonstration of its applicability done on the NARSIS standard design plant model, showing the use for evaluation of DiD and DEC. Demonstration required an enormous computational effort that simply could not have been done few years ago due to limited computational capacities at that time. Further application of E-BEPU for validation of SAMGs has also been elaborated.

Works, carried out in close cooperation between NARSIS WP3, WP4 and WP5, have demonstrated the potential of this novel approach, being probably one of the first attempts to show how both, deterministic and probabilistic methods can be combined to bring a truly integrated method for safety assessment of the design of nuclear installations.

The main contribution of E-BEPU to nuclear safety is in introducing stricter requirements on successful sequences in safety analysis and thus avoiding possible cliff-edge effects. On the other hand it provides certain relaxations for extremely unlikely sequences under certain conditions when these sequences can be treated as “practically eliminated”.

4.5 Summary

Improving the integration of external hazards and their consequences with existing state-of-the-art risk assessment methodologies was the objective of WP3 of the NARSIS project. The work followed three main themes:

- An investigation of the use of BNs, focusing on delineating the advantages and challenges as compared to more traditional probabilistic safety assessment techniques such as FTs.
- Developments in constraining uncertainties. Uncertainties remain in all probabilistic safety assessment, especially in industries characterised by high reliabilities and therefore have little data available on failures. Developments focused on the ability to identify the most influential sources of uncertainty and novel methods to reduce them.
- Advances in the E-BEPU method and evaluation of its behaviour regarding defense-in-depth and design extension conditions.

This report has presented the main contributions in terms of the activities, developments and findings.

5 Applying and comparing various approaches for safety assessment

5.1 Main objectives

The first objective of WP4 was to develop and apply model reduction strategies for assessing the impact of external hazards on the fragility of critical systems/components from a probabilistic viewpoint. Attention was first focused on metamodeling strategies (aka response surface, surrogate models) for risks associated with earthquake and tsunamis events. Metamodeling is widely used in structural reliability modeling, aircraft industries, and in different domains of natural hazard assessment (landslides, coastal flooding, earthquakes). Based on approximate input-output relationships, metamodeling allows for PSAs. Since these works imply performing many expensive computations, efforts have also been put on the development of a novel solving strategy for complex, highly nonlinear dynamic structural systems, which could be used for fragility assessment. Based on the Proper Generalized Decomposition (PGD) and the Large Time INcrement (LATIN) method, this strategy allows deriving virtual charts related to the NPP units' dynamic response and including parameters associated with the seismic loading features.

The second objective was to apply and compare new and existing methods for deterministic, probabilistic and combined probabilistic-deterministic analyses, for plant scale reactor safety analyses. This was to be done for a referential (generic or virtual) Generation-III NPP defined in the NARSIS task4.1 hereafter.

Both objectives were addressed within three main tasks and related main deliverables provided hereafter:

- Task 4.1: Definition of a simplified theoretical NPP representative of the European fleet

  This resulted in deliverable D4.1 (Bruneliere et al., 2018).

- Task 4.2: Model reduction strategies for external hazards events

  This task includes the following deliverables:

  - D4.2 (Zentner et al., 2020): description of two seismic-oriented and one tsunami metamodeling strategies for probabilistic analyses;
  - D4.3 (coming in 2022): description of a novel model reduction strategy for complex, highly nonlinear and dynamic systems, based on the Proper Generalized Decomposition and LATIN approaches;
  - D4.4 (coming in 2022): applicability of model reduction strategies in safety analyses

- Task 4.3: Nuclear Power Plant Safety Analysis

  This resulted in D4.5 (Darnowski et al., 2021).

5.2 General outcomes

5.2.1 Metamodelling strategies for probabilistic analyses

Two seismic-oriented and one tsunami metamodeling strategies were investigated for probabilistic analyses in the frame of WP4. They are described in deliverable D4.2 (Zentner et al., 2020).

5.2.1.1 Seismic risk assessment

The metamodeling methodology developed by Wang et al. (2018a,b) is based on Artificial Neural Networks (ANN) for the construction of metamodels to build the relations between seismic IMs and Engineering Demand Parameters (EDPs) of the structures, to accelerate the fragility analysis (Figure 18). Fragility curves can then be evaluated using direct Monte Carlo simulations by assuming a lognormal model and applying linear regression techniques. The methodology allows for vector-valued fragility curves.

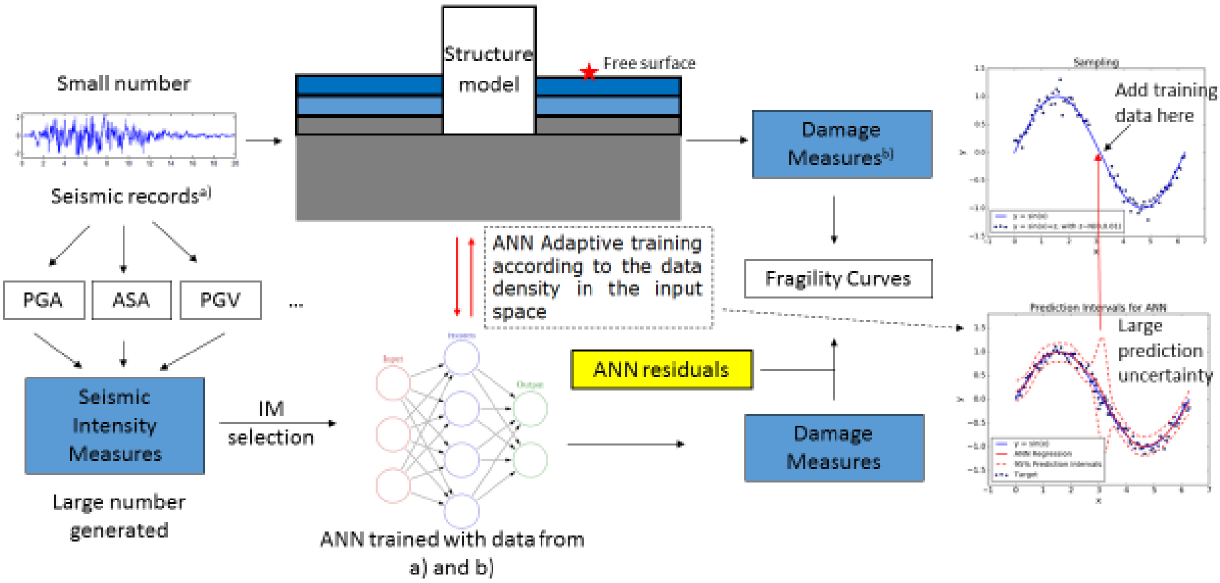


Figure 18: Schematic representation of the methodology

The quantification and investigation of the ANN prediction uncertainty are computed with the delta method. It consists of an aleatory component from the simplification of the seismic inputs and an epistemic model uncertainty from the limited size of the training data. The aleatory component is integrated into the computation of fragility curves, whereas the epistemic part provides the confidence intervals. In numerical simulations, a set of N time histories is used to obtain a sample of N EDPs. The collection of the corresponding IMs is determined from time histories. This data is used to train the ANN. Once the ANN is trained, new data can be simulated at negligible cost by sampling IMs (e.g., using Ground Motion Prediction Equations - GMPEs) and determining the respective EDPs. To best explore the space of possible model parameters while reducing the number of computations, the fragility curves are determined by an adaptive ANN procedure. Figure 19 illustrates an example application showing that adaptive learning better explores the space of interest: more failures and better-distributed results. This methodology has been successfully applied to estimate the probability of failure of an electrical cabinet in a reactor building studied in the framework of the KARISMA benchmark.

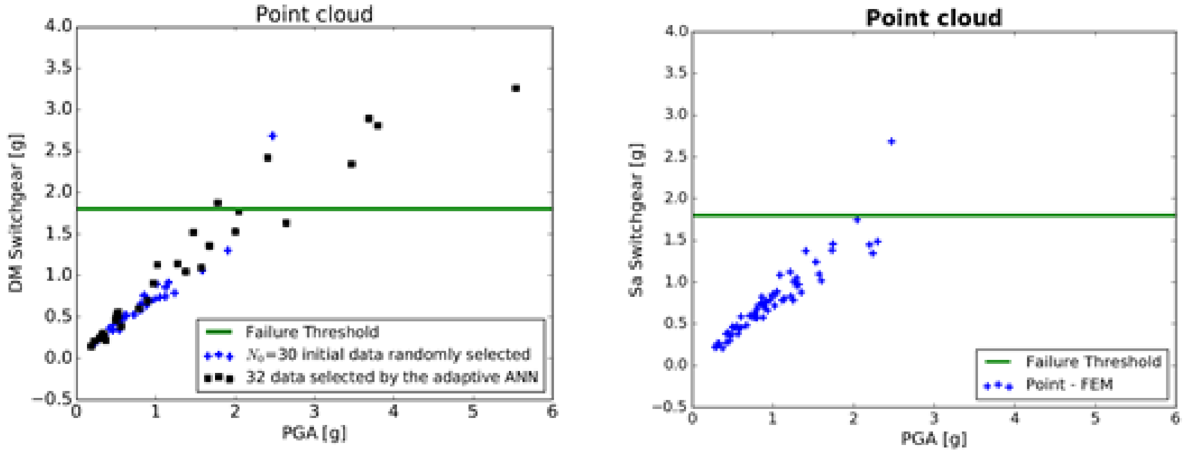


Figure 19: Adaptive learning (left) and random samples without adaptive learning (right)

The second methodology developed by Sainct et al. (2018) is based on Support Vector Machines (SVMs) coupled with an Active Learning algorithm. This methodology adopts SVMs to achieve a binary classification of structural responses relative to a limit threshold of exceedance. Since the SVM output is not binary, but a real-valued score, a probabilistic interpretation of this real-valued score is introduced to estimate fragility curves very efficiently.

The first step of the proposed methodology consists of generating a set of artificial seismic signals and computing IM indicators of interest. In this work, a collection of acceleration records selected in a real ground motion database based on magnitude and distance criteria (Ambraseys et al., 2000) was enriched. To this end, the parameterized stochastic model of modulated and filtered white-noise process defined in Rezaeian and Der Kiureghian (2010) was used. After signal generation, the second step of the methodology consists of building an SVM-based classifier by optimally selecting by active learning the mechanical calculations to perform. Finally, a probabilistic interpretation of the real-valued score given by the classifier is used (in a third step) to estimate fragility curves as score functions. In addition, one can show that the classifier can also predict the scores and probabilities associated with several new input parameters to estimate fragility curves as functions of the classical seismic IMs (PGA, etc.).

Different procedures can construct empirical fragility curves (see, e.g., Mai et al., 2017). This methodology assumes that they are merely evaluated based on k-means clustering of the IM data. In a Monte Carlo-based approach, this means that in each cluster, the empirical probability of failure corresponds to the ratio between the number of structural responses that exceed the limit threshold and the cluster size, i.e., the number of structural responses belonging to the cluster.

5.2.1.2 Earthquake-induced tsunami hazard assessment

A kriging approach (e.g., Roustant et al., 2012) was developed to construct metamodels for earthquake-induced tsunami hazard assessment, accounting for uncertainties on the scenario parameters, namely the epicenter location, the rupturing fault size and the slip displacements. The selected technique enables to learn in a non-parametric manner, the statistical link between the scenario parameters and the tsunami hazard IM, namely the maximum Sea Surface Elevation (SSE) at the coast.

A first round of numerical simulations was performed to evaluate the capabilities of the proposed method on a test case located in the Liguria Sea. It was based on a total of 300 long-running hydrodynamic simulations conducted in a former French research project (http://www-tandem.cea.fr/), considering the historical worst-case scenario of the 1887 earthquake. On this basis, kriging metamodels were constructed considering different critical locations along the coast. A leave-one-out cross-validation procedure was conducted to confirm the predictability of the different metamodels. These validated kriging metamodels were then used in place of the long-running simulators within a Monte-Carlo setting to evaluate the cumulative probability of SSE given the uncertainties on the worst-case scenario.

5.2.2 Novel model reduction strategies for fragility analyses

As already mentioned, the complexity and richness of the numerical models used to predict the often nonlinear behavior of structures generate computation times of several days for the simulation of a single seismic event using classical Newmark-like incremental methods. Furthermore, assessing the margins and taking into account the variability of the reference problem parameters lead to making this numerical effort, no longer for the simulation of a single model but of a family of models. Considerable work was thus devoted to deriving a strategy for computing parametric solutions, also called *numerical charts*, for nonlinear dynamics in the low-frequency range (typical seismic inputs have a frequency content below 50Hz), and this with the idea of minimizing the associated computational cost. This work is described in the PhD narrative of Rodriguez-Iturra (2021) and in deliverable D4.4.

Among the different strategies dedicated to the resolution of parametric problems, some methods, released in the 2000s and currently booming, propose to use an ingredient referred to as *model-order reduction*, which confers them a formidable numerical efficiency. The main idea is to exploit the redundancy of information in the parametric solution to propose an approximated and numerically efficient resolution of the problem, which guarantees that the calculated approximation, called low-rank approximation, stays close enough to the real solution. The reference problem solution is thus approximated by a sum of *M* terms where each is a product of functions with separate variables. The integer *M* is called the rank of the approximation, and, in practice, the approximation space is constructed incrementally. Among other model-order reduction techniques, the *Proper Generalized Decomposition* (PGD) (Ladevèze, 1999) offers a conducive framework for obtaining parametric solutions in the linear range (see, e.g., Ammar et al., 2006; Gunzburger et al., 2007; Chevreuil and Nouy, 2012). In turn, the LATIN method proposes a general solving strategy for nonlinear problems in mechanics involving an alternative sequence of *nonlinear* and *linear stages*.

The derived method was tested on several numerical examples involving damaging quasi-brittle (e.g., concrete) and elasto-viscoplastic (e.g., steel) materials. Figure 20 compares the results obtained when simulating the dynamic response of a 6m concrete beam supported by moving supports using classical step-by-step integration (Newmark scheme for time integration and Newton-Raphson algorithm for nonlinearity) and newly derived LATIN/PGD methodology. The results with both methods are in good accordance and the CPU time is slightly (about 30%) in favour of the LATIN/PGD method.

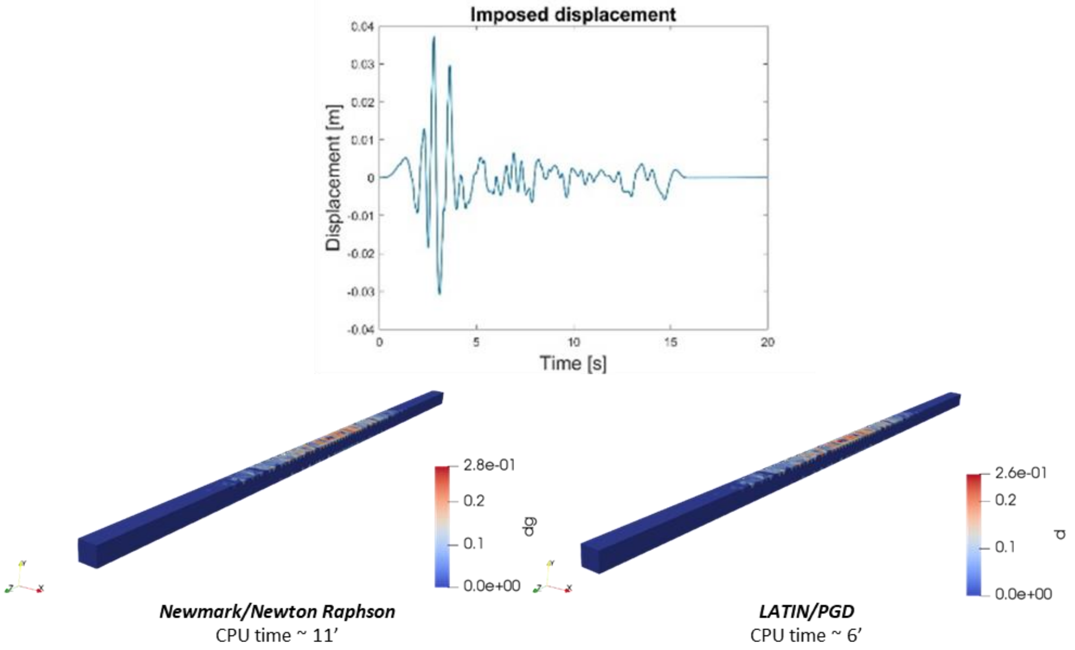


Figure 20: Reference calculation – First comparison between classical step-by-step and LATIN/PGD resolution in dynamics. A simply supported 6m concrete beam meshed with 4535 linear tetrahedrons and integrated on 20s with 1000 Lagrange polynomials of order 2 in time has been submitted to a dynamic motion of the supports. The time histories confront the damage obtained at most loaded Gauss point for the two approaches and the complete 3D damage field is given at the end of the two simulations for comparison.

A parameterized solution was then computed, considering the elastic properties of the material and the loading amplitude varying in +/-40% intervals. Thousand (1000) LATIN/PGD simulations have been run where the solution S_{i+1} for a parameter θ_{i+1} is initiated to an already converged solution S_i associated to a close parameter set θ_i to decrease the number of LATIN iteration needed for convergence. Compared to chained classical step-by-step resolution, the computational gain is estimated to be more than 700% in favor of the LATIN/PGD approach when performing such parametrical studies.

Once the parameterized solution is computed, probabilistic studies can be performed for negligible computational cost by simply interrogating/interpolating the numerical charts. Figure 21 shows an example of the fragility curves that can be obtained "quasi-instantaneously".

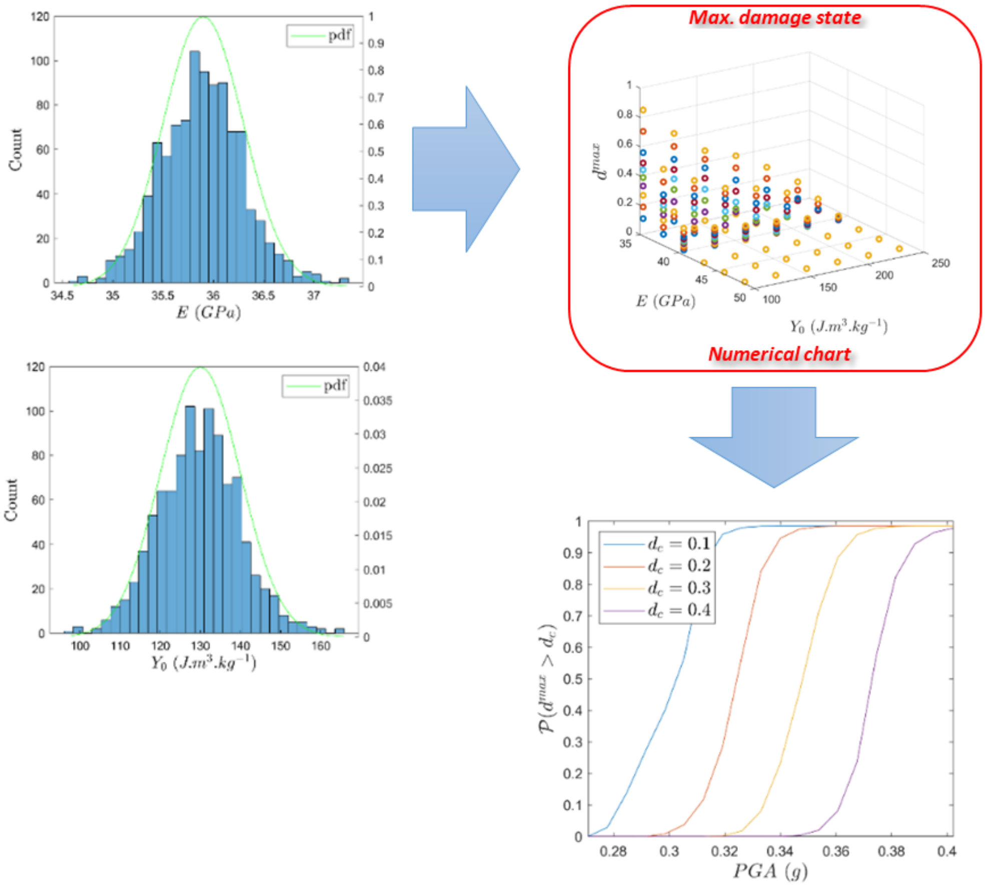


Figure 21: Parameterized solution – Maximum damage state obtained for the beam of Figure 20 as a function of the Young's modulus E and damage activation threshold Y_0 varying in a +/- 40% interval. This numerical chart is then used for computing fragility curves (probability of failure $(d_{max} > d_c)$ where d_c is a given damage threshold) by simple interpolation.

5.3 Reactor safety analysis, considering deterministic and probabilistic approaches

5.3.1 General overview

Figure 22 presents the map of connections between different topics and activities performed in the task4.3 of WP4, as well as the connections to other project contributions and WPs.

Works were based on the referential Generation-III NPP defined in D4.1 (Bruneliere et al., 2018),which was used as a virtual plant to develop, test, and demonstrate various aspects and progress in NARSIS. They are fully described in the deliverable D4.5 (Darnowski et al., 2021), and cover three main areas:

- 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 5ET) in case of single and multiple hazard scenarios;
- Combined probabilistic-deterministic analysis (E-BEPU), which was applied for the first time in safety analysis.

Different topics were studied, including sensitivity and uncertainty analysis with more traditional and global approaches. A new methodology was presented for coupling structural analysis with severe accident analysis to study the aging phenomena impact during a severe accident in NPPs. A severe accident analysis with source term investigation was also conducted on the reference Gen-III plant, virtually located on a Polish nuclear site.

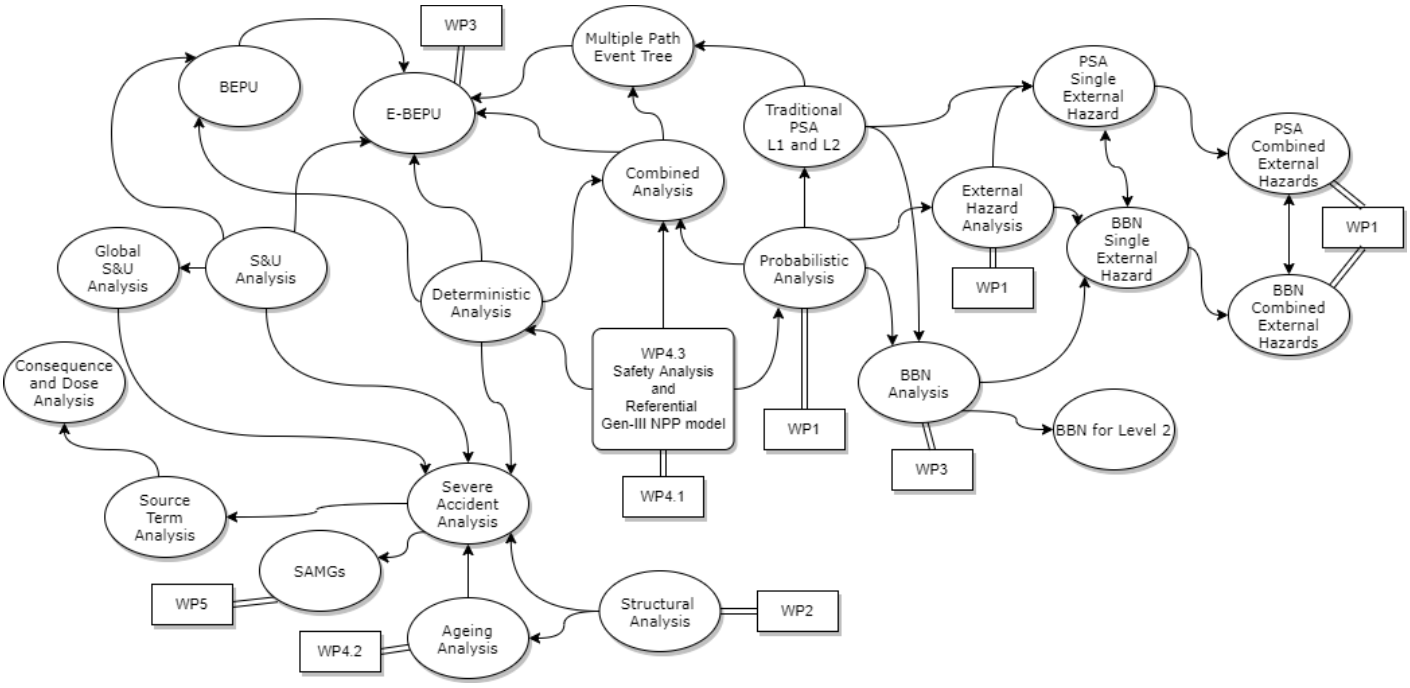


Figure 22: Map of connections and activities in the NARSIS WP4.3, including internal couplings and external couplings to other WPs.

5.3.2 Combined Deterministic and Probabilistic Methods – E-BEPU

The E-BEPU methodology aims to demonstrate the existence of larger safety margins that could be utilized for more extensive operational flexibility or plant modifications for power uprates, design life extension, and similar. At the same time, 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) for which traditional methods are weaker. In addressing sequences that fulfill the regulatory acceptance criteria with a standard tolerance level (STL), additional, more stringent requirements are placed to eliminate any possibility for cliff-edge effects. On the other hand, for certain sequences that do not fulfill the regulatory acceptance criteria (RAC) with the STL, but have a low enough probability of occurrence, reclassification into a higher class is allowed, where they are compared to the acceptance criteria of that class (or some other more stringent criteria) but with a stricter, new level of acceptance. According to the current licensing bases, the "single failure criterion" is mandatory in designing safety systems as a vital constituent of defense in depth. However, the design verification analysis with E-BEPU is relaxed (not eliminated). On the other hand, a combination of failures, sometimes more likely and potentially more harmful than the worst single failure, are taken into consideration.

The common feature of the conservative, best estimate (BE) and best estimate plus uncertainties (BEPU) analyses is that conservative assumptions are made about the availability of safety systems. The single failure criterion stipulates that the safety-related systems shall also perform their safety function in the event of any single failure. This principle can be applied either to safety systems composed of redundant trains or to diverse systems designed to perform the same safety function. In using this principle in the deterministic analysis of a two-train safety-related system, one train is conservatively assumed to be unavailable. In other words, the probability that a particular train of a safety system is available can only take two values, namely 1 or 0, and there must be one train assumed failed. The main point of E-BEPU is to provide a more realistic and more flexible solution by quantifying the probability that a specific train will be available or unavailable and not simply assigning the probability to 0 or 1 in an E-BEPU analysis. Different combinations of available safety system trains are analyzed and adequately weighted with their respective probabilities.

This approach is not entirely new. The same idea has been proposed already in the US standard ANSI/ANS-51.1 and German standard KTA-SG-47. Both standards bring the idea that for certain sequences coming from the same postulated initiating event (PIE), different acceptance criteria can be applied, given that their conditional probability of occurrence is low enough. Based on their conditional (given the occurrence of the PIE) probability of occurrence sequences can be classified in different plant states (PS) where different acceptance criteria may apply for different parameters.

Notice that the main features of E-BEPU make it highly consistent with the newest IAEA Safety Requirements on Design of NPPs, SSR 2/1 Rev. 1 in its Requirement 42 para 5.73, which requires that safety analysis shall assure safety margins, avoidance of cliff-edge effects and early and large radioactive releases. Demonstration of available safety margins and assurance that there are no cliff-edge effects is explicitly addressed in the E-BEPU methodology.

The E-BEPU methodology map flowchart is given in Figure 23. It is a complex framework with several steps (blocks). Each of them covers various activities which combine deterministic and probabilistic methods. This procedure was applied, tested, and demonstrated with plant scale analysis for the first time. Such work demanded performing probabilistic analyses with PSA tools (Sapphire, Risk Spectrum) and thermal-hydraulics analyses with best-estimate system code for plant simulations (RELAP5). A novel Multiple Path Event Tree (MPET) approach was also proposed to perform a probabilistic study with PSA code for the E-BEPU. In the context of the deterministic analysis, several thousands of RELAP5 runs were executed with substantial computational effort. The considered design successfully passed the procedure. For the sake of comparison, a more traditional BEPU-like study was also performed, and a comparison with E-BEPU was presented.

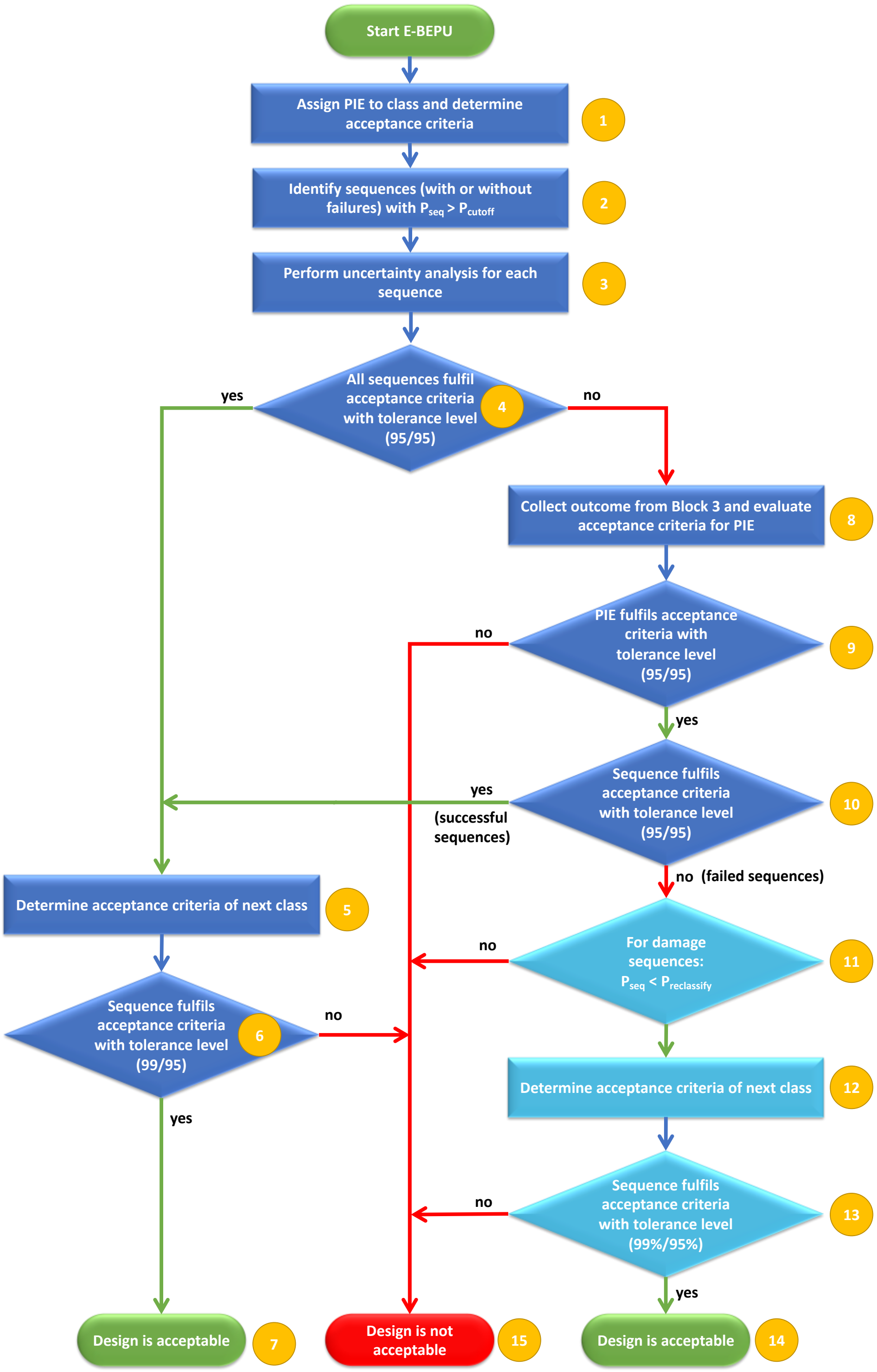


Figure 23: The E-BEPU methodology flowchart.

5.3.3 Fully Probabilistic Methods - BN and PSA

5.3.3.1 PSA approaches for combined earthquake and flooding hazards

The following scenario was selected to apply the PSA and BBN methods:

(i) LOOP (Loss Of Offsite Power, defined as loss of electrical supply from the primary and auxiliary power grid to plant switchgear) has occurred following one or more external hazard events;

(ii) During the LOOP situation for an extended time, at least one Emergency Diesel Generator (EDG) is needed; therefore, all four EDGs failures would lead to a partial Station Black-

Out (SBO) situation. In addition, total SBO will happen if additional two Ultimate Diesel Generators (UDG) fail

(iii) The Secondary Cooldown (SCD) system is actuated if a partial SBO occurs. SCD needs to assure that at least one out of four Steam Generators (SG) will be used for residual heat removal (RHR) or partial cool down (PCD).

The PSA models developed here were based on the NPP PSA model of WP4, extended to consider earthquake, flooding and their combination.

The first step for the proper creation of multiple-hazards probabilistic safety assessment according to the methodology presented in Figure 24 is the identification of potential hazards for the facility (here, earthquakes and flooding). The second step concerns the definition of an accident scenario. In the third step, the ET/FT of the Safety Systems for considered accident scenarios are created. For performing this step, fragility data for each component are needed. In this step, CCF from the basic model (no external hazards included) has to be considered.

Once basic ET/FT are created, external hazards can be included in the PSA studies. Hence, in the considered case, seismic FT (technically as model type) can be created, and FT for the flooding event can be modified from Safety Systems FT based on the elevation of the equipment and possible flooding range (expressed in terms of the height of water level). The total failure probability for combined hazards can finally be obtained.

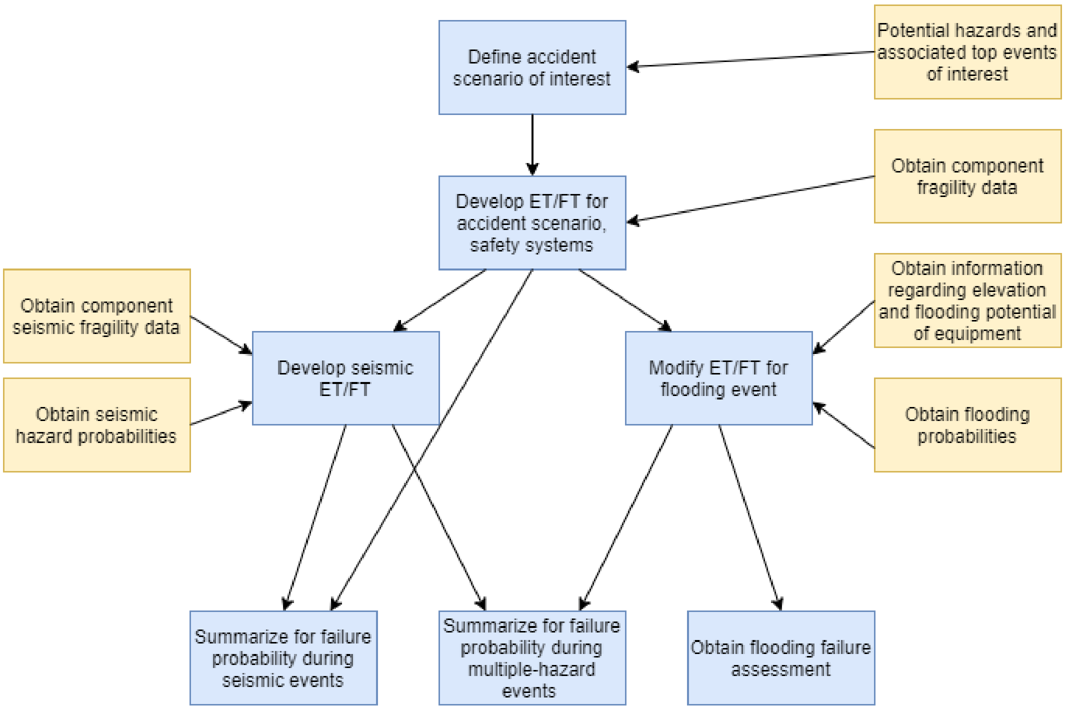


Figure 24 General methodology for multiple-hazard PSA (earthquake + flooding)

The performed studies revealed that:

- 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.

5.3.3.2 Comparison of BN and PSA approaches for combined earthquake and flooding hazards

BNs were studied and developed for the accident scenario described in the previous section. They included subnetworks developed for the LOOP with the SBO tree, the SCD11 tree. Comparisons between FT and BN methods were performed, including a new approach to CCF modeling using BNs. The BN method was then applied based on subnetworks developed for SBO and SCD11 trees. An example of BN and PSA models is presented in Figure 25.

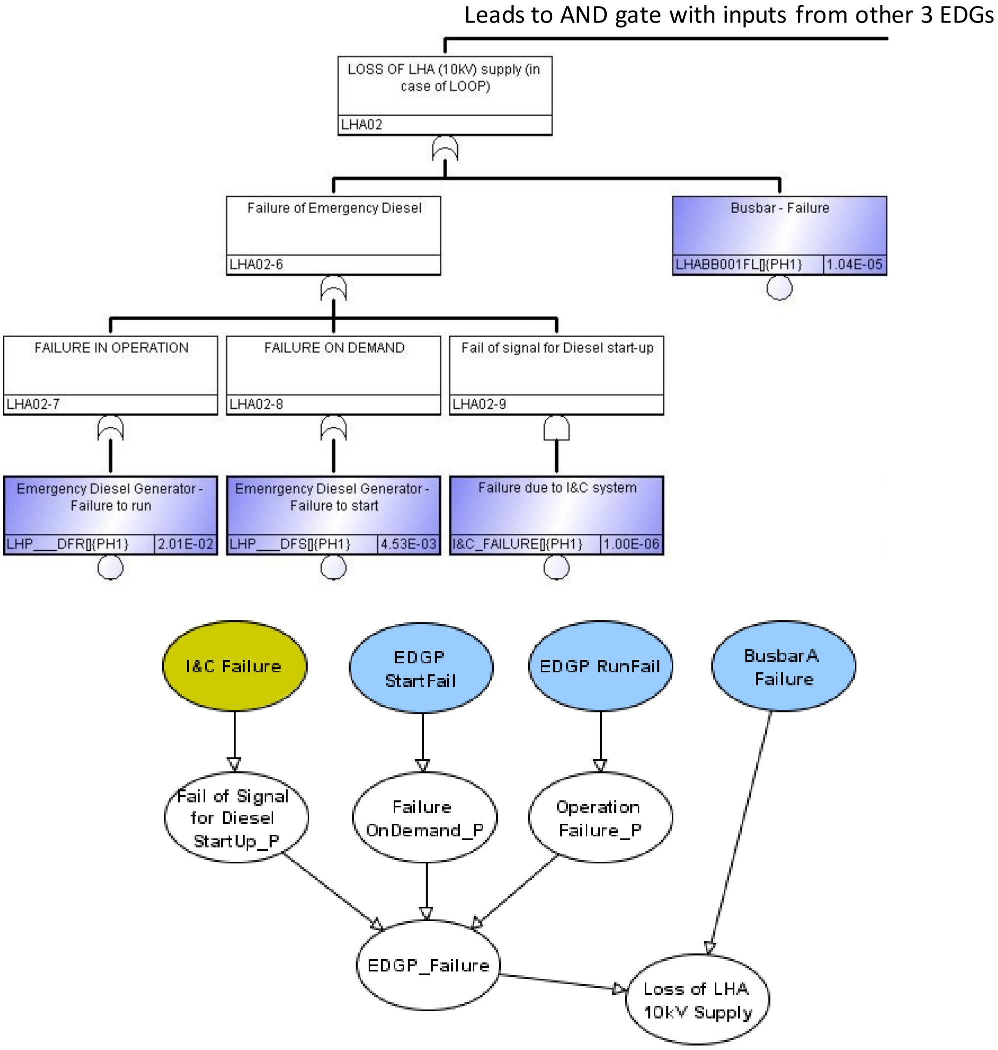


Figure 25 Left: Part of fault tree depicting the loss of one of four emergency diesel generators during a LOOP scenario (SBO fault tree). Right: corresponding BN.

The more traditional PSA approach developed for the multi-hazard scenario involving earthquake and flooding events was also implemented using BNs. In D4.5, the application of the BN method for the SBO scenario involving multiple hazards is compared with the PSA approach. The obtained BN model is presented in Figure 26.

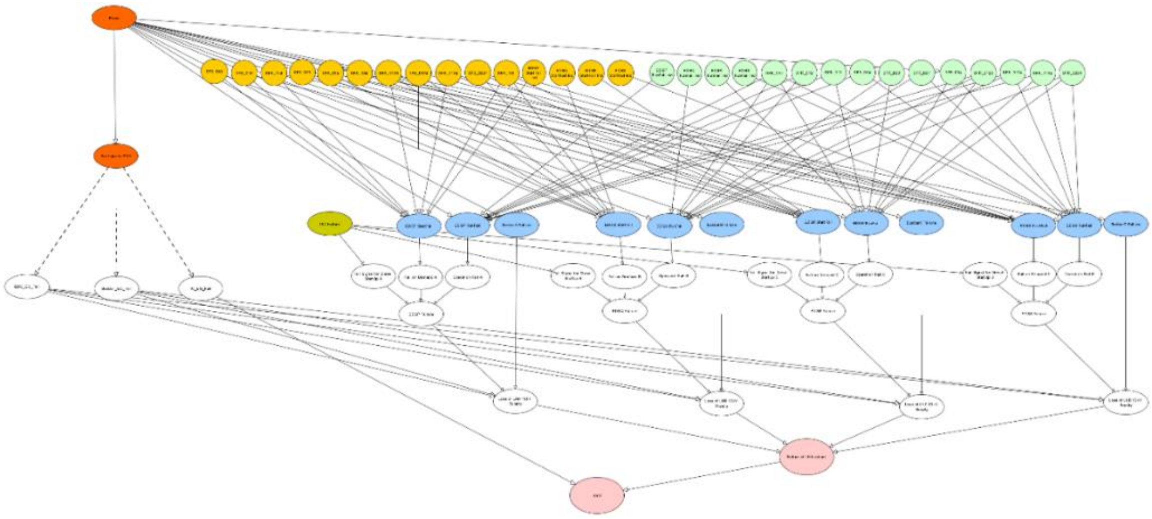


Figure 26: Unified BN model including all multi-hazard scenarios.

Both approaches can generally achieve identical results but have some differences. Based on implementations of the SBO scenario, the following conclusions can be drawn:

- Since the FT may be considered as a specific, deterministic case of a BN, probability estimates obtained from traditional PSA approaches can also be derived from the BN approach. 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.
- The posterior joint probability of all basic events given top event occurrence provides information regarding both occurrence and non-occurrence of all the basic events. Hence, 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.
- Importance measures used in traditional PSA follow the same trend as posterior probability estimates obtained from BNs, conditional on system failure. For instance, the FV measure of components (or cutsets) is identical to posterior probabilities from the BN when evidence of system failure is input to the network.
- Multi-state variables can more directly be incorporated into BNs. The number of entries in conditional probability tables (CPTs) increases exponentially with the number of states, making BN construction and computation arduous. However, assumptions such as the *Noisy OR*, can significantly offset this issue. As observed in the multi-hazard case, the use of multi-state variables is particularly useful in combining scenarios into a unified BN, rather than using several hazard trees and summing their probabilities. While using several hazard trees, dependencies may be missed between different variables across scenarios. Using a unified BN could possibly limit such omissions.
- If required, subnetworks may also be created for each hazard tree instead of a unified BN. The interactions between subnetworks can be defined using object-oriented BNs (OOBNs). This can aid visualization.
- BNs inherently consider statistical dependencies between variables. Hence, the consideration of CCFs is easily included at the level of CPTs without modifications in network structure. Nevertheless, parametric models for implicit common cause effects can be modeled (as in the traditional PSA approach) by converting fault trees with CCF events into BNs.
- BNs can directly incorporate continuous random variables without the need for additional modifications, as in the case of fault trees. Also, it is easy to integrate expert

judgment in BNs. These advantages were demonstrated under the LOOP-induced SBO and SCD_11 scenario in the deliverable D3.2.

- In BNs, logical interactions between events and components are not visually represented, as in fault trees, but are hidden within conditional probability tables.
- As more complex systems are modeled, 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. An alternate approach is proposed in this study for considering CCFs in BNs, to curb the proliferation of nodes and links due to CCF events. The accuracy of this alternate approach needs further examination.

5.3.3.3 PSA approaches for combined wind-related hazards

In addition to the hazard combinations addressed previously, a PSA modelling example on hazard combinations related to high wind was investigated. High wind-related LOOP were modelled with heavy snowfall, frazil ice and algae. In each case, the probability of the other hazards given high wind was estimated based on fictive but realistic weather data and/or expert judgments. The probability estimates were developed separately for each month to consider the seasonal correlations between hazards explicitly. The LOOP frequency due to high wind was divided between the months based on wind data. The frequencies of the hazard combinations were estimated for each month. Finally, the monthly frequencies were summed up to calculate the annual frequencies.

Combinations of three hazards were also included in the analysis. The hazard combinations were modelled in the NARSIS reference plant PSA model using FinPSA software. It was done by extending the existing ET models of LOOP and LUHS (Loss of Ultimate Heat Sink) scenarios. The hazard impacts were modelled using the hazard table of FinPSA, which maps the hazards automatically to the correct places in FTs. The combination of high wind and heavy snowfall was the most critical hazard combination in the results, though the numbers were fictive. It was also seen that combinations of three hazards are sometimes more critical than combinations of two hazards. A comparison between FTs and BNs was also performed, based on the model. The conditional core damage probabilities calculated by PSA and BNs were approximately the same.

5.3.3.4 BN in Level 2-PSA

Specific issues related to the application of BNs in level 2 PSA were considered. These issues are the interface between PSA levels 1/2 and the modelling of severe accident phenomena. Indeed, there are typically some dependencies between PSA levels 1 and 2. Safety functions in levels 1 and 2 may be dependent (e.g., due to common power supply system), and fault trees in levels 1 and 2 may have some common parts. Therefore, level 2 PSA cannot be performed independently, but the dependency on level 1 needs to be considered in the calculations. When fault trees are used, the dependency can be taken into account by using level 1 minimal cutsets as inputs to level 2. With BNs, a similar approach does not seem plausible unless minimal cutsets are solved from the BNs (i.e., BNs are used in the same way as fault trees). Instead, BNs combining the safety function failures from levels 1 and 2 could be generated in the same way that a fault tree for an accident sequence can be generated by combining the fault trees of the safety functions that fail in the sequence. BNs of all sequences leading to the same plant damage state would thus need to be combined. This would lead to very large BNs, and therefore, a very powerful BN solver would be necessary in addition to software functionality to automate the process.

Severe accident phenomena can be modelled in different ways in PSA. The computation of physical phenomena is often performed in background analyses, and only a single basic event or event tree branch probability is used in the PSA model (e.g., for containment failure due to steam explosion). Slightly more complex modelling is possible using FTs. However, FTs have limited capabilities to represent physical phenomena because those are associated with continuous variables. The multi-state logic of BNs is an advantage in this area, though also discrete BNs have limited capability to represent physical phenomena. Conversely, BNs with continuous variables would enable complete modelling of continuous variables but would also be computationally much more demanding. Probabilistic intermediate nodes also make BNs more compact than fault trees.

5.3.4 New Methods in Deterministic Safety Analysis

A new deterministic methodological approach was proposed to model aging effects during Severe Accidents. It is based on integrating severe accident integral code and a Finite Element (FE) code (Figure 27-left). The first code predicts the response of the whole plant subjected to a postulated severe accident scenario and provides the boundary conditions for the second code. The FE code predicts the thermo-mechanical response of the selected components. The MELCOR2.2 and MSC©MARC codes for postulated SBO accidents were used to study the Reactor Pressure Vessel (RPV) response. Studies of the impact of aging, mainly material obsolescence and thermal degradation, and creep phenomena were carried out. Representative results are shown in Figure 27-center. The adopted methodology was verified based on the FOREVER/C1 experiment for both 2D and 3D models (Figure 27-right).

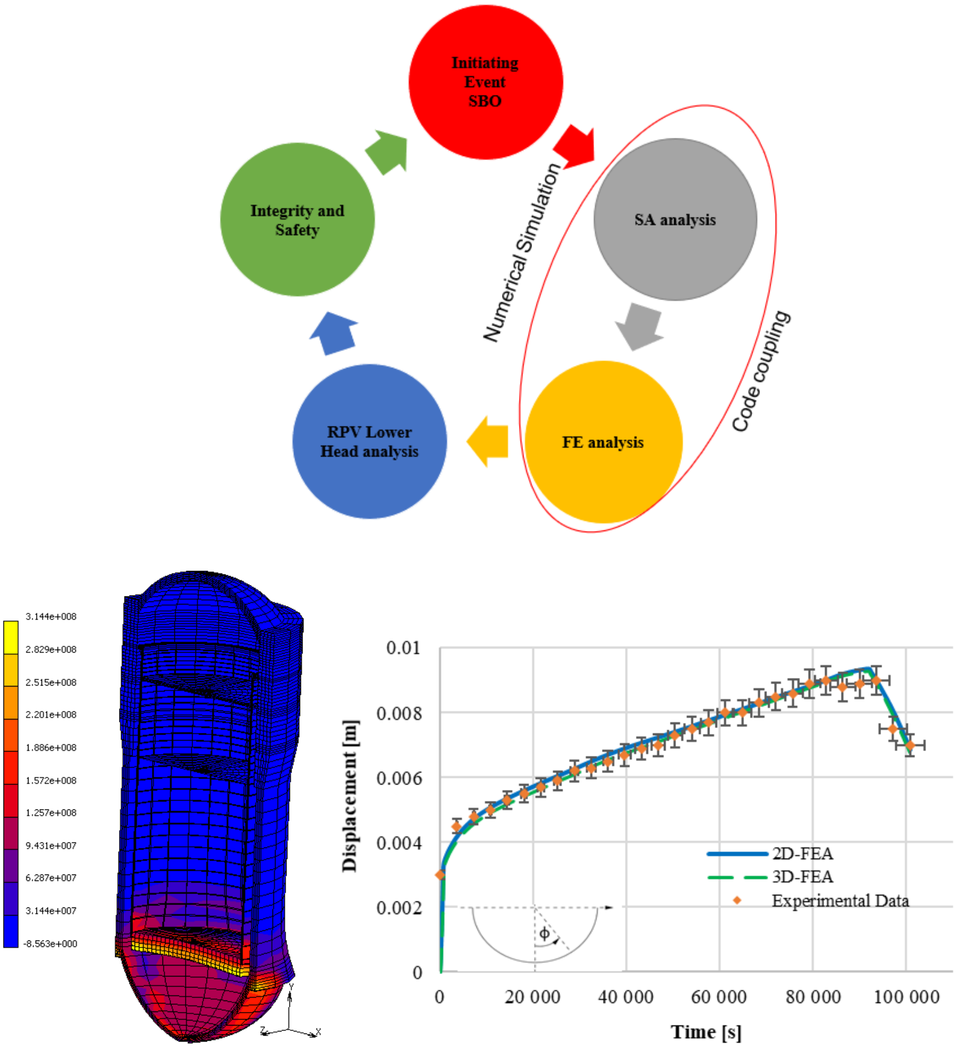


Figure 27 Top: Methodological approach for a severe accident with thermo-structural analysis and aging assessment. Bottom-left: Example of Von Mises stress distribution for RPV deformed shape. Bottom-Right: FOREVER/C1 experiment FEM code verification.

5.3.5 Sensitivity and Uncertainty Analysis with Standard and Global Approaches for Severe Accident Applications

Several methods for Sensitivity and Uncertainty Analysis (S&UA) were presented. The demonstration case was the Gen-III referential NPP during an unmitigated LB-LOCA accident. Analyses were prepared with MELCOR code. The focus was put on the in-vessel hydrogen generation phenomena. The standard approach to UA with the Wilks method was compared with the Monte Carlo approach with many models. The impact of uncertainty parameters and random sampling methods were studied. Results were compared with Phebus FPT-1 experiment. It was shown that there is little difference between Simple Random Sampling and Latin Hypercube Sampling for a large number of input decks. It was also shown that the uniform probability distributions provide fewer conservative results for the considered problem. Additionally, a new Matlab open-source tool for S&UA with MELCOR was developed.

A new BIGUSA global sensitivity and uncertainty approach was tested with the NPP plant scale problem for the first time. The method uses Sobol indices to find sources of uncertainty, including interactions between input variables. It was compared with the Wilks approach. It can be observed that in the case of uncertainty analysis, it provides comparable results to the standard approach, but with a much larger statistical sample as thousands of MELCOR runs were executed. As expected, the observed marginal values were higher and lower than in Wilks-based calculations, as more outliers were sampled. In the case of sensitivity analysis, the global approach can also provide similar answers when considering linear regression analysis, which was applied in this study. However, it was shown that the Wilks-based calculation was relatively ineffective in finding weak correlations, whereas the BIGUSA approach was more reliable. For BIGUSA sample is several times larger than in the case of Wilks. This work shows that the main power of BIGUSA is Sobol indices, which allow evaluating the impact of uncertainty parameters onto final uncertainty using the first order, the second-order, and total Sobol indices. It allows quantitative and qualitative assessment of sources of uncertainty and interactions between those sources. It is unique for Global methods because the typical approach with basic Monte Carlo and Wilks does not allow it simply.

5.3.6 Selected Severe Accident Studies for the Gen-III Referential Plant

The outcomes of various severe accident studies for referential Gen-III NPP were presented. All simulations were performed for LOOP IE during full-power operation with consequential total SBO. The LOOP with SBO is one of the probable consequences, which can occur due to the external hazard and can result in core damage for some sequences.

The MELCOR model for Gen-III NPP was used to simulate the response to a severe accident. This model was built for both the in-vessel and ex-vessel phase of the accident to evaluate the source term. The analysis for in-vessel progression with the study of the thermal hydraulics, core degradation phenomena were presented. In the next stage of the work, simulations for the ex-vessel phase with containment performance and corium concrete interactions were developed. Studies covered the response of the core melt stabilization device, which is the main element of the NPP's ex-vessel melt retention strategy. Parametric sensitivity simulations were performed for different heat transfer ex-vessel options. Studies have shown that the considered design is robust in ex-vessel melt stabilization for the long time interval.

Then, a source term was investigated. Two containment rupture models were considered, namely the best estimate (BE) with leak type rupture and conservative rupture model. It was shown that the best estimate model predicts about two orders of magnitude lower releases at the moment of the rupture. In a longer time scale (about one day after the rupture), the BE model predicts one order of magnitude lower releases compared to the conservative case. The outcomes were compared with reference data for Gen-II SBO (from WP5), and it was shown that the Gen-III plant is characterized by at least one order of magnitude lower releases during the total SBO. Moreover, the timescale of release is shifted by several days compared to Gen-II design, providing much more time for mitigation actions.

5.3.7 Severe Accident Analyses for SAMGs in the Gen-II Referential Plant

In the framework of the WP5, a Gen-II referential NPP was studied, which can also be considered as generic. Contrary to the WP4 plant, SAMGs were defined at a high level of detail for decision-making (DM) demonstration purposes. The MELCOR model for the Gen-II NPP was also developed and the experience gained during simulations of the Gen-III PWR reactor with MELCOR, as well as the modelling practices and methods developed in WP4 were applied in WP5. The modeling outcomes of these activities are summarised in D4.5. The accident analysis was performed for about thirty scenarios with the various operator and SAMG actions. The results were applied to generate a database of plant states needed to demonstrate, test, and develop the SAMG DM tool SEVERA (cf. WP5 section).

5.3.8 Radioactive Releases and Consequence Studies

Finally, the environmental radioactive release analysis and consequence estimations were performed based on the severe accident results. It was prepared with MACCS2 computer code. A realistic NPP site was selected in the vicinity of a large city in Poland. In the analysis, conservative environmental conditions were selected based on real meteorological data for the considered site. The source terms based on the total SBO scenario studied all along WP4 for the Gen-III referential NPP showed minimal consequences for the population. It proved substantial robustness of the considered NPP design.

6 Decision-Supporting tool for Severe Accident Management

6.1 Main objective

In order to bring NPP to a safe state and minimize radioactive releases to environment and public during an accident, several measures are used. In NARSIS, we first characterized external hazard events and their combinations (WP1), and performed appropriate fragility assessment of the main NPP critical elements (WP2). Various safety assessment approaches (WP4) were developed and tested for the safety assessment of generic PWR plants (WP3), based different multi-hazard integration methods (WP3). Although the NPP has the SSCs to prevent severe accidents, it needs also to have the resources for coping with severe accidents and is for this purpose provided with dedicated SSCs and guidelines for operators and technical support center (TSC). There is a very small probability for severe accident to appear. However, it can still happen, even if the best practices are employed in the NPP design and operation. The main objective of WP5 was hence to develop a demonstrative decision support tool for severe accident management, in order to make appropriate decisions in a timely manner. Such a tool, if fully developed and implemented, would be a novelty in NPP. It would not be a substitute to the people in the TSC. However it would provide additional information which can be used to speed up the decision process and make it more informed. During the course of an accident, the tool would:

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

This objective was addressed within four main tasks and related main deliverables provided hereafter:

- Task 5.1 - Characterization of the referential NPP

  This resulted in deliverable D5.1 (Debelak et al. 2018a).

- Task 5.2 - Characterization of Emergency Operating Procedures, Extensive Damage Management Guidelines, FLEX and Severe Accident Management Guidelines

  This resulted in deliverable D5.2 (Debelak et al. 2018b).

- Task 5.3 - Definition of hazard-induced damage states and development of state-specific APETs for demonstration purposes

  This task resulted in D5.3 (Vrbanić et al. 2019).

- Task 5.4 - Development of supporting SAMG DM tool for demonstration purposes

  This task resulted in D5.4 (Bohannec et al. 2021), D5.4bis (Darnowski et al. 2021) and D5.5 (Dusic & Hortal, 2020).

6.2 General outcomes

In the first step of WP5, we defined a “referential” plant in terms of critical systems and structures, as described in the deliverable D5.1. The level of characterization had to be limited in a way to suffice for the purpose of demonstration of the supporting decision tool for severe accident management (SAM). The referential NPP had two loops, large dry containment and safety systems for design basis, and design extension condition (DEC) accident management, including severe accidents (Figure 28).

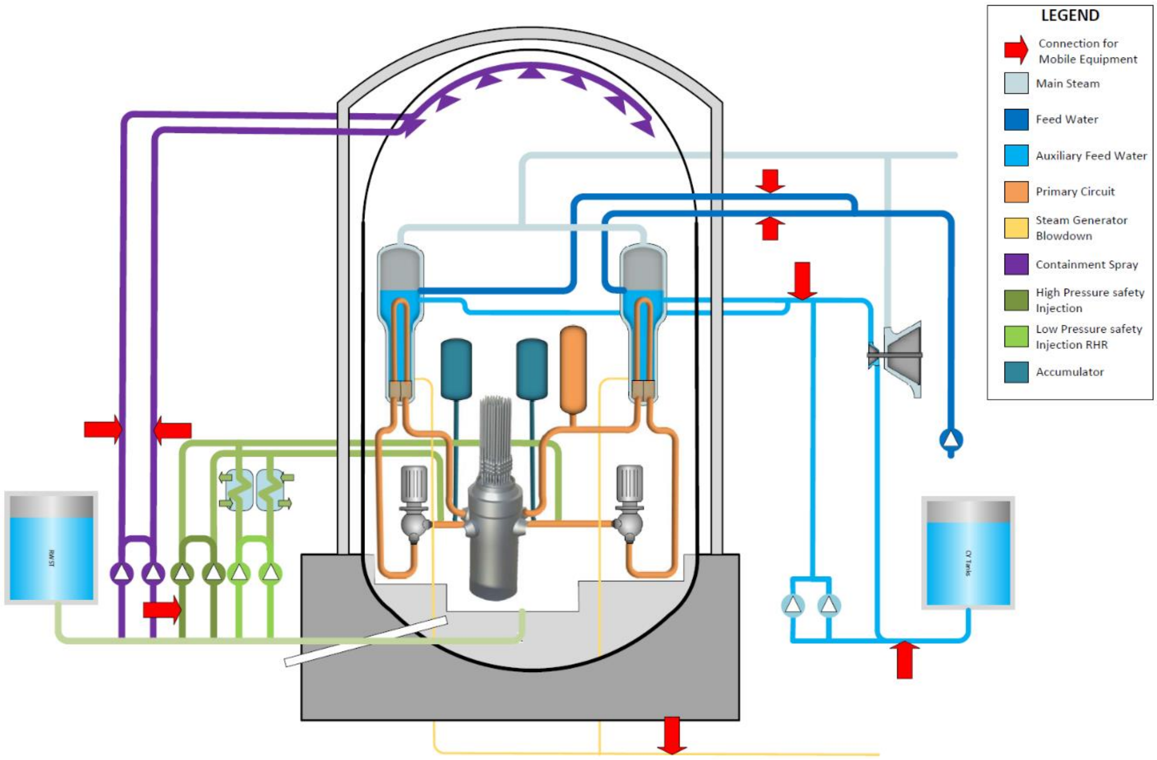


Figure 28 Reactor coolant system of the referential NPP with safety systems and connection points for mobile equipment.

In the second step, we characterized simplified, “referential”, Emergency Operating Procedures (EOP), Extreme Damage Management Guidelines (EDMG) and SAMG (Severe Accident Management Guidelines) to be followed by plant operators and Technical Support Center responsible staff under the postulated severe accident sequence. This work is described in the deliverable D5.2.

In the next step, we established the hazard damage states and the logic model for accident progression, to be used as a basis for the mentioned supporting tool. This work is documented in the deliverable D5.3.

The accident progression logic structure was developed in the form of ETs and similar techniques, such as event sequence diagrams for the postulated set of hazard damage states (Figure 29). The main plant functions and corresponding systems related to hazard damage states were identified as follows:

- Reactor Coolant System Depressurization,
- Low Pressure (LP) Emergency Core Cooling Injection,
- LP Emergency Core Cooling Recirculation,
- Containment Spray Recirculation, and
- Containment Cooling.

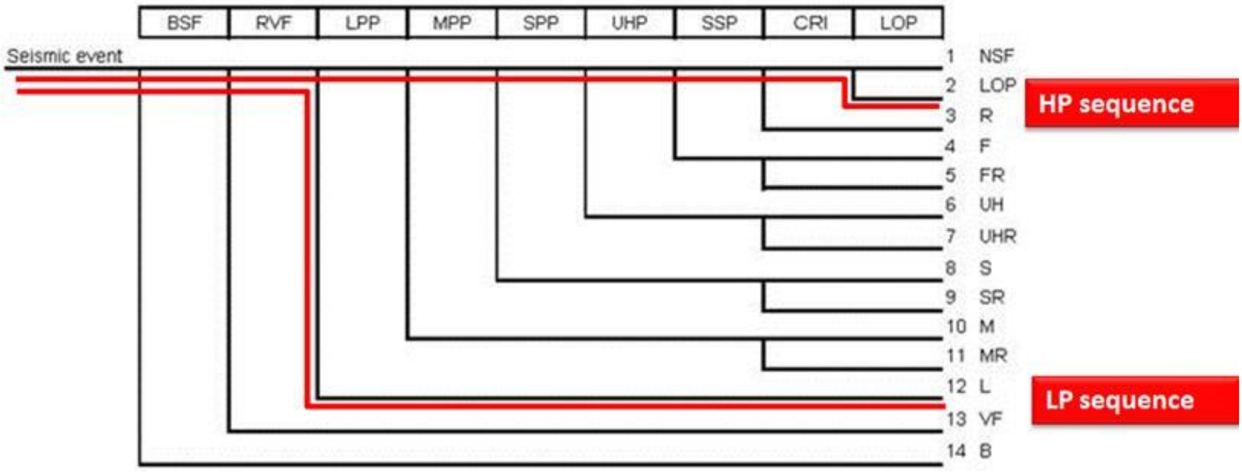


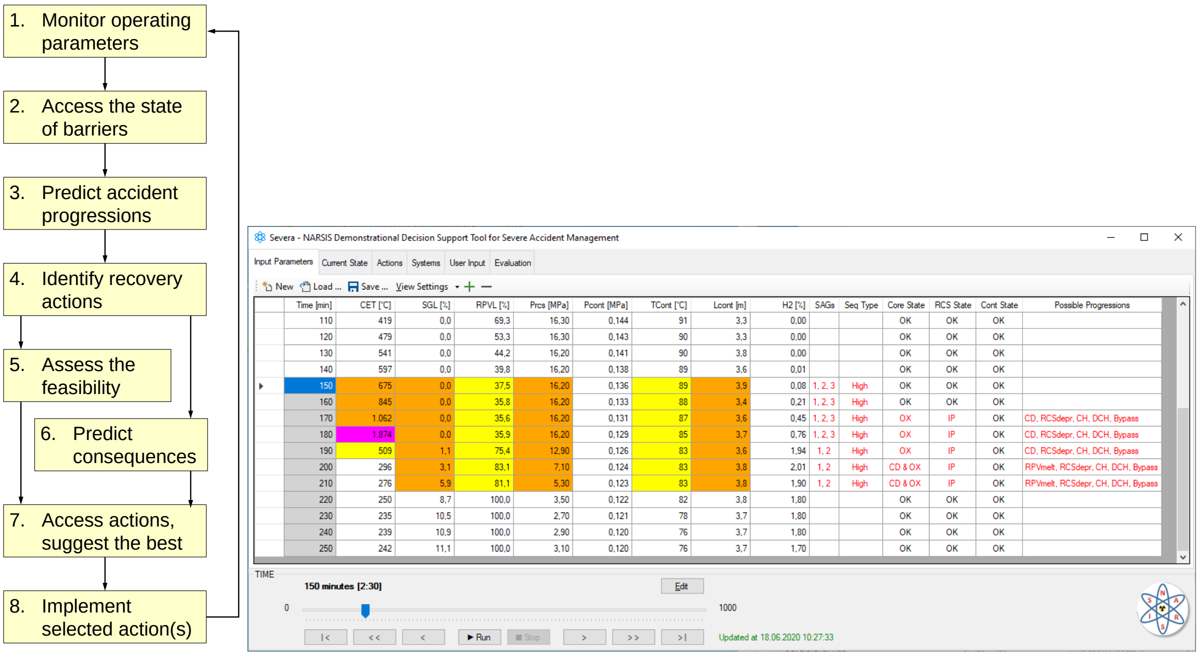
Figure 29 Example Logic Model for Seismically Induced high pressure (HP) and low pressure (LP) Sequence.

We identified and characterized the types of decisions and actions to be made under the SAM, to be considered by the supporting tool.

The supporting SAMG DM tool for demonstration purposes is the main outcome of the WP5. In order to analyze the situation in the NPP, deterministic models were developed in computer program MELCOR. The MELCOR simulations for both in-vessel and ex-vessel phases for different accident scenarios were performed. More than 25 accident sequences were studied and used for the SAMG DM tool. The results are documented in an extra-report D5.4bis (Darnowski et al., 2021).

The decision modelling (DM) was developed by establishing logic and functional model for attributes for each alternative (decision path) and establishing utility function and decision rules. The functional requirements and conceptual architecture were developed, followed by the development of the software modules and decision/evaluation models.

The DM computer program is called Severa and is described in the deliverable D5.4. Its flow chart is presented on Figure 30. In principle, the idea is that the program would be used interactively by the TSC team. The operation would take place in cycles that would begin with observing and interpreting the measured parameters, continue with assessing the state of plant systems (core, RCS and containment) and predicting possible progressions of the accident, and end by formulating possible management actions and assessing their consequences in terms of probabilities of radioactive release categories. At the end of the cycle, the TSC team would be expected to decide which management action(s) to actually take, if any. A typical duration of one such cycle is assessed to be at 10 to 20 minutes. The main steps of the interactive process are outlined in the diagram shown in Figure 30.



Time [min]	CET [°C]	SGL [%]	RPVL [%]	Prcs [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	

150 minutes [2:30]

Updated at 18.06.2020 10:27:33

Figure 30 Severa flow chart (left) and display of a time series of NPP main parameters together with barrier states determined by Severa (right).

The same figure also shows an example of Severa's display related to the first three steps of the diagram. The displayed table contains a time series of measured key plant parameters. The time sequence of key plant parameters is inserted to the program either by the user "as the accident progress" or by loading one of the predefined scenarios. Individual measurements are interpreted using colours that indicate the severity of the measurement in the context of the accident. The table also presents the assessment of barrier states and prediction of accident progression. These are determined using a hierarchical rule-based model, developed according to the multi-criteria method DEX.

In the next steps, Severa supports the identification of possible recovery actions and assesses their feasibility and effectiveness with regard to the likelihood of radioactivity releases. The consequences of actions are predicted by Severa by assessment based on the accident progression event tree.

Hence, the Severa decision-support tool consists of two main parts: diagnostic and prognostic. The purpose of the diagnostic part is to establish basic facts about the status of the severe accident sequence, based on the feedback in the form of a set of pre-selected parameters. The prognostic part has the purpose to support the user in evaluating existing options / alternatives for accident management and mitigation, depending on the diagnosis and on the available means, and to select the best one or to rank the options / alternatives. In doing this, the prognostic part of the tool does not interfere with the hierarchy or priority of the actions or instructions which are deterministically postulated in the Severe Accident Management Guidelines (SAMGs). The prognostic part of the tool would assist the user in identifying those actions which can be implemented, under their predefined priorities, in a way which would result with the smallest risk from radioactivity release to the environment.

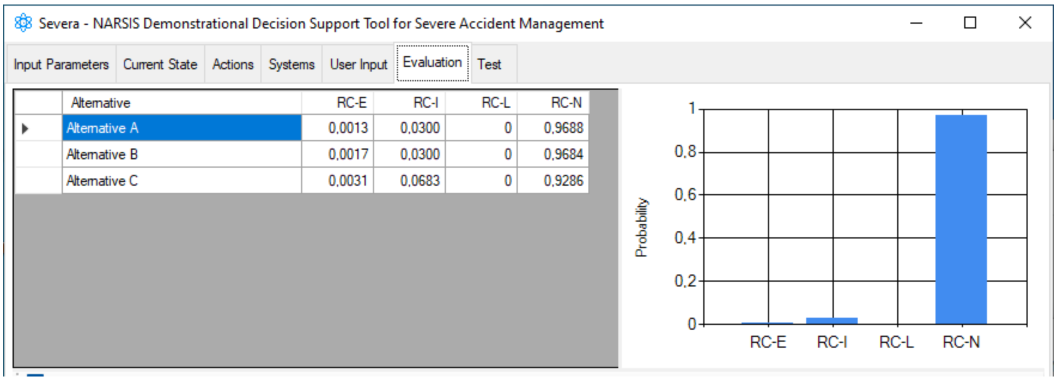
The core of the model implemented in the prognostic part of Severa is the above mentioned accident progression event tree. Branching points are related to high-level actions (HLAs). HLA are main actions of SAMG and essentially define the plant status:

- Inject into SG,
- Depressurize the RCS,
- Inject into the RCS and
- Actions related to containment integrity.

Alternatives are different “success paths” with their associated “time delays”. The main results of the prognostic part of Severa are given in a way that for each considered “alternative” Severa provides the conditional probabilities of predefined radioactivity release categories, as a result:

- RC-E Early containment failure / radioactivity release,
- RC-I Intermediate containment failure / radioactivity release,
- RC-L Late containment failure / radioactivity release and
- RC-N Long-term concern about radioactive release.

Figure 31 shows an example of assessing three possible decision “alternatives” and displaying a chart of expected radioactive releases, which provides the main basis for choosing the best management action.



Alternative	RC-E	RC-I	RC-L	RC-N
Alternative A	0,0013	0,0300	0	0,9688
Alternative B	0,0017	0,0300	0	0,9684
Alternative C	0,0031	0,0683	0	0,9286

Figure 31 Evaluation of decision alternatives in Severa in terms of probability distributions of radioactive release categories.

Severa was extensively verified and validated, showing that it can provide reasonable predictions of probability profiles of predefined release categories for the scenarios considered.

It needs to be pointed out that Severa is still a simplified tool which was developed in order to investigate the possibilities of this kind of support for decision-making in severe accident management, primarily for the training purposes of NPPs TSC staff. As any simplified tool, it has its limitations. Among the most important is the treatment of time dependency of the probabilistic parameters incorporated in its prognostic logic. A number of phenomenological probabilities are presented by values which apply at an early phase of scenarios and, therefore, their use is limited to this time window. Furthermore, it relies on simplified presentation of logic models for “success paths” and system functions, as well as simplified consideration of adequacy of equipment included in the model and feedback from the implemented actions.

Altogether, it can be said that this demonstration version of Severa is capable of assessing the risk reduction potential of available mitigating actions based on expected time windows for equipment recovery and predetermined probability profiles of predefined major radioactive release categories for different plant statuses / configurations. The appropriate timely executed operator actions should reduce the early containment failure potential or/and minimize other types of radiological releases. The TSC staff decisions based on additional information and training with Severa can lead to better understanding and management of severe accidents in nuclear power plants.

Further research and development in order to address the current limitations and simplifications can be done in parallel with a thorough assessment of applicability of Severa for practical purposes. This can be done by investigating the possibilities to use Severa as an educational tool for training the TSC staff and formulating the requirements and assessing the resources necessary to integrate a tool such as Severa to the information-technology support of a real-world NPP.

Apart from the Severa development, WP5 additionally included the activities related to the application of the E-BEPU method in the development and V&V of SAMG involving the LB LOCA reclassification. The work is documented in D5.5. The main feature of E-BEPU is to extend the scope of the uncertainty analysis typical of BEPU to include uncertainty in the configuration of the safety systems that are activated in the course of the accident.

Although the verification of the design of safety features provided for SAM is always a difficult task, E-BEPU allows for a feasible approach to such verification. It can provide additional insights that can be used for the development and V&V of SAMG, especially by identifying possible cliff-edge effects on one hand and by identifying very unlikely event sequences on the other hand that can be tolerated based on their unlikely occurrence, meaning that in some cases they can be treated as “practically eliminated”.

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