METIS

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Recommendations to conduct seismic PSA

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Summary

The deliverable D7.10 is devoted to overview the results of the following Tasks: ? Development of an open-source representation format for PSA models; ? Development of a dedicated seismic database management tool; ? Development of new assessment algorithms; ? Validation, verification and benchmarking of the new tools; ? Application of new assessment methods to METIS study case; as well as to identify future needs with regards to METIS tool and model improvements, and future seismic PSA research.

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Summary of WP7 activities
Deliverable D7.10

Version N°1

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Abbreviations and Acronyms

Acronym	Description
AS	Accident Sequence
BE	Basic Event
CCF	Common Cause Failures
CCDP	Conditional Core Damage Probability
CDF	Core Damage Frequency
DG	Diesel generator
ET	Event Tree
EQ	Earthquake
FDF	Fuel Damage Frequency
FT	Fault Tree
HDS	HRA Damage States
HEP	Human Error Probability
HRA	Human Reliability Analysis

IE	Initiating event
LOCA	Loss of coolant accident
LRF, LERF	Large Release Frequency, Large Early Release Frequency
MCS	Minimal cutset
OPSAMEF	Open-PSA Model Exchange Format
PGA	Peak Ground Acceleration
POS	Operational States
PSA	Probabilistic Safety Assessment
RC-ESDOF	Reinforced Concrete (Structure) – Equivalent Single Degree of Freedom
SPSA	Seismic Probabilistic Safety Assessment
SSC	Systems, Structures and Components
WWER	Water-Water Energetic Reactor
WP	Work Package
ZNPP	Zaporizhzhia NPP
XML	eXtensible Markup Language

Summary

The deliverable D7.10 is devoted to summarize the results of the following Tasks:

- Development of an open-source representation format for PSA models;
- Development of a dedicated seismic database management tool;
- Development of new assessment algorithms;
- Validation, verification and benchmarking of the new tools;
- Application of new assessment methods to METIS study case;

as well as to identify future needs with regards to METIS tool and model improvements, and future seismic PSA research.

Keywords

Seismic PSA; METIS tool; core damage frequency.

Introduction

The main objective of the METIS project is to further develop the tools and methodologies used in seismic safety assessments (PSA) of nuclear power plants.

This task focuses on overview and summarizing the results of the work package 7 activities, identifying future requirements for METIS code and model enhancements, and exploring future research directions in seismic PSA. Detailed technical information on tools used and methods applied is documented in associated deliverables (see Bibliography).

The general view of WP7 tasks and interfaces with other work packages of the METIS project are shown on Figure 1.

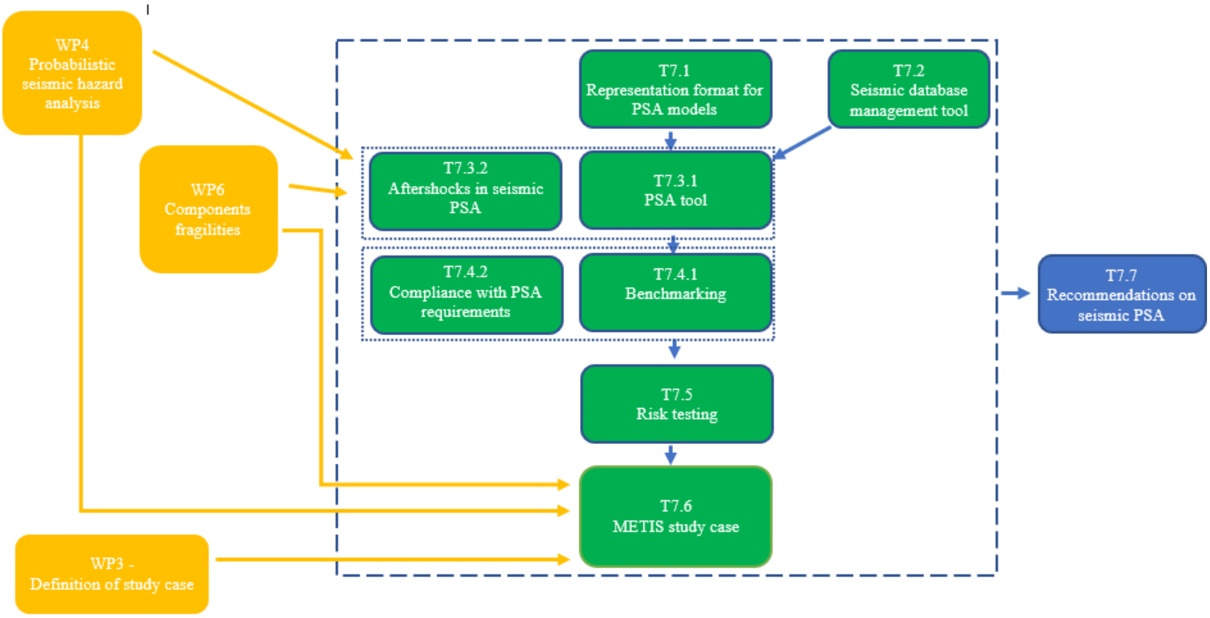

Figure 1: Flow chart of the METIS work package 7

The main technical elements of SPSA are /IAEA 2020/:

1. Probabilistic seismic hazard assessment;
2. Development of seismic equipment list;
3. Seismic fragility analysis;
4. Seismic plant response analysis;
5. Seismic risk quantification and interpretation of results.

This deliverable deals with the probabilistic part of SPSA – development of seismic equipment list, probabilistic modelling and quantification. As part of work package WP7, the METIS tool for probabilistic safety assessment modelling has been developed and benchmarked. This tool integrates multiple software components within a unified calculation framework for seismic PSA. It utilizes the SCRAM code for Boolean computations and includes METIS software for defining fault trees and event trees, along with a user interface. Additionally, a specialized tool was developed to prepare data on seismic failure probabilities to be included in PSA models. After performing set of benchmarking calculations, the METIS tool has been used to model the METIS case study, and to quantity seismic core damage frequency for selected seismically-induced initiating event. During development of the METIS case study, new approaches related to modelling aspects with high uncertainties have been implemented and/or tested.

Based on the results of the METIS tool development and the METIS study case modeling, several lessons have been learned and discussed in this deliverable.

Section 1 presents the METIS tool components.

Section 2 deals with presentation of seismic PSA approaches that have been considered or modified in the framework of WP7.

Overview of the METIS study case probabilistic model developed using the METIS tool, along with the results of calculations are presented in Section 3.

Section 4 represents interpretation and discussion of the WP7 results.

Section 5 contains conclusions.

1. The METIS tool

Commercial PSA tools used in nuclear industry have their own proprietary format to represent models. This situation, inherited from the historical development of tools and market conditions, constitutes a real barrier to the introduction of new tools and methods and more generally to innovation in the domain. The Open-PSA initiative, /OPSA 2017/, an informal group of academic and industry experts, proposed an open-source, standard representation format for fault trees and event trees. This format, Open-PSA Model Exchange Format (OPSAMEF), has been extensively tested and adapted in several commercial and non-commercial tools. OPSAMEF deals with structured XML (eXtensible Markup Language) format intended to address main issues on PSA models, such as:

- Quality assurance (quantification of models by different software);
- Over reliance on numerical approximations and truncation;
- Portability of the models between different software;
- Clarity of the models;
- Completeness of the models;
- Modeling of human actions;
- Better visualization of PSA results;
- Difficulty of different software working with the same PSA model;
- Lack of data and software backward and forward compatibility;
- No universal format for industry data.

Architecture of OPSAMEF is illustrated on Figure 2.

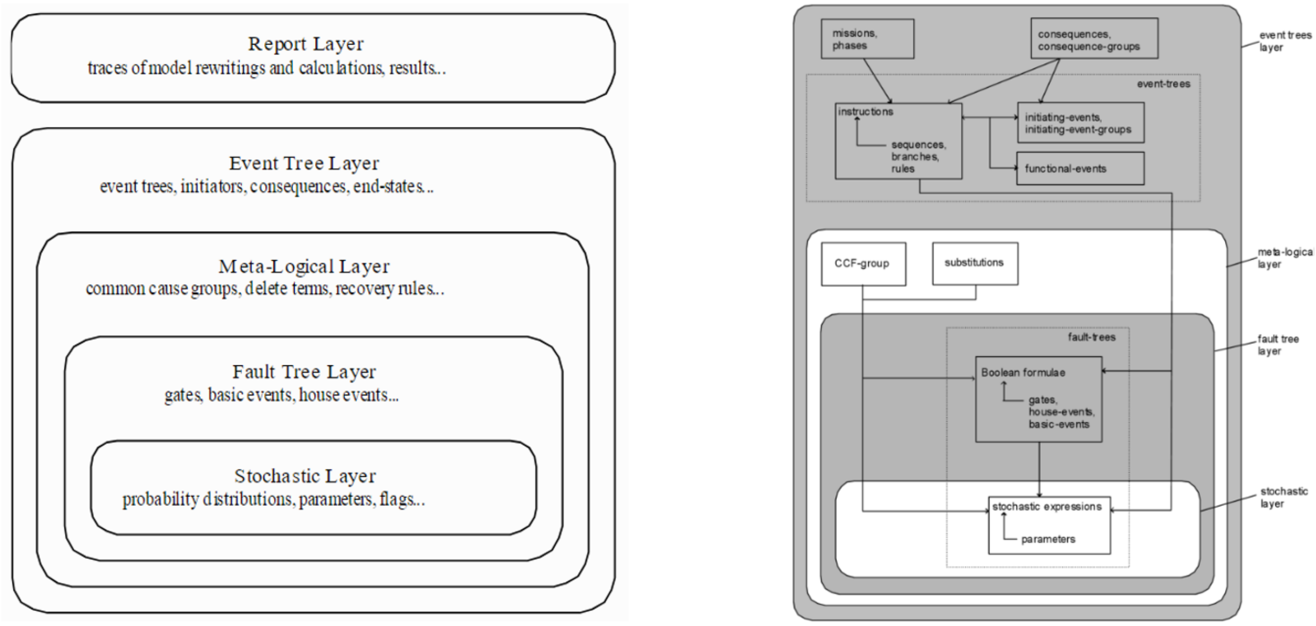

Figure 2 OPSAMEF architecture, /OPSA 2017/

The expected benefits of this new representation format: portability of models, validation of models, cross-verification of results, openness to innovation, etc. Within a seismic PSA, it can be an essential tool to exchange models, to incorporate fragility curves and to implement model rewriting techniques.

The main needs of the seismic PSA models to extend the OPSAMEF have been reviewed and discussed as part of development of the METIS tool, /METIS 2022/. M. Hibti, /METIS 2022/ have proposed several modifications to the OPSAMEF in order to facilitate the generation of one or several structure function which truncation is adequate to the level of seismic risk studied; to propagate uncertainties in an efficient manner while the sampled basic events probabilities remain adequate with the truncated structure function:

- define a format to modify the probability of some basic events (in our case the ones related to seismic failure of systems, structures, or components - SSC) before the generation of the structure function. By this way, the minimal cut set (MCS) generated is suitable to assess the risk when the probability of SSC failure is close to the one transmitted before the structure function generation despite its possible truncation,
- define a format to transmit new probabilities for some basic events (corresponding, in our case, to uncertainty propagation) used to reassess the risk after the structure function generation.

With this approach, the probabilities of seismically induced failures (for several discrete intervals defined by the analyst or for all the spectrum of possible mechanical solicitation) would be generated by an external tool (see Section 1.3) that takes into account the correlation between SSC failures.

Taking into account /METIS 2022/ developments, the METIS tool was drafted and further benchmarked. The general architecture of the METIS tool is presented in Figure 2.

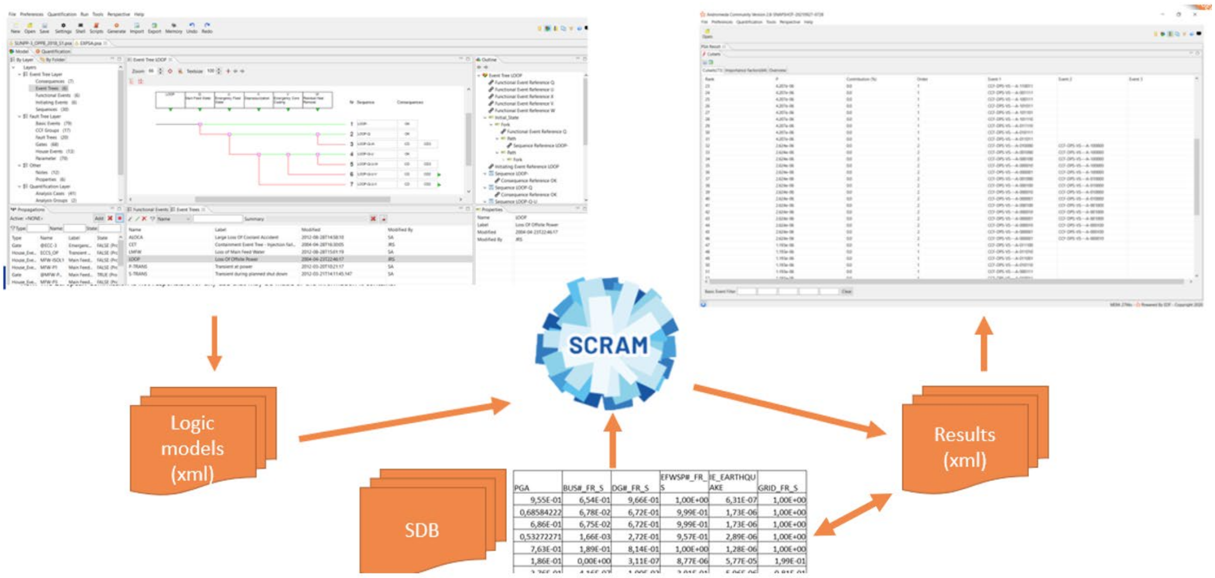

Figure 3 The METIS tool

The METIS tool consists of several modules, each of which can be used independently, as a stand-alone tool: coupled Andromeda-SCRAM tool, Seismic Data Base tool, Uncertainty propagation tool.

The METIS tool for PSA probabilistic modelling has been benchmarked, /METIS 2024b/. The benchmarking results demonstrated a strong correlation between calculation done be the METIS tool, and software SAPHIRE, and RiskSpectrum PSA software, indicating that using similar input data and modelling approaches can produce reliable results for the METIS. However, minor differences were observed between the METIS tool and SAPHIRE, which can be attributed to SAPHIRE's sensitivity to the rounding of the SSC capacity parameter (Am) when calculating seismic failure probability.

1.1. Andromeda software

The vital part of the METIS tool is Andromeda - a software tool developed by EDF for probabilistic risk modeling and assessment. Andromeda also can serve as a research environment for testing and evaluating new risk assessment methods and approaches. It utilizes OPSAMEF and follows the modular concept, effectively addressing the challenge of increasing complexity through modularization and instantiation techniques. Modularization breaks down complex models into smaller, manageable modules, enhancing control and clarity. Meanwhile, instantiation enables the adaptation of a generic model to various contexts, ensuring flexibility and applicability. Together, these strategies significantly streamline risk assessment and improve model efficiency.

Andromeda is constructed in a modular fashion with a central core and different modules each providing a different capability, as follows (see Figure 3):

- **PSA model editing**: it allows to edit a model by creating and modifying event trees, fault trees, parameters, etc.
- **Model comparison**: it allows to compare two models. For each type of object (basic event, event tree, fault tree, analysis case) Andromeda provides the details of the difference in a graphical as well as in a textual form.

- **Model fusion**: it allows to merge two models after comparing them. Andromeda requires a model A, model B and a base model (that can be one of the two previous models). Andromeda can merge the model A with the model B. In case of conflict (different versions of the same object with respect to the base model), Andromeda asks the user to fix the conflict by selecting the option A or B to be considered into the merged model.

- **Version management**: it allows to use the git platform for the version management of the PSA model. The version management can be done either locally or from/to a remote repository. The version management allows to keep track of all the model modifications, have multiple analysts working simultaneously on the same model (thanks to the branch concept), restore the previous correct version in case of error, *etc*.

- **Scripting**: Andromeda has a Jython API. This means that it provides the user with a set of functions that can be used into a script for model modification. The use of scripts is particularly recommended in case of massive and repetitive modifications.

- **Documentation**: for several elements of the model, Andromeda allows the user to fill up a wiki page. In this way the user can write the documentation at the same time as the model construction. This capability also helps to keep the documentation updated coherently with the model changes.

- **Dependency and Cartography**: this module provides the backward and forward dependency of each model element. For example, for a given basic event, the forward dependency provides the parameters that are associated to the basic event, while the backward dependency provides all the fault trees, function events, event trees, etc. that make use of the considered basic event. A cartography is also provided to show the dependencies in a more visual way, and may be used to split large study cases in a coherent manner to perform parallel computation if needed.

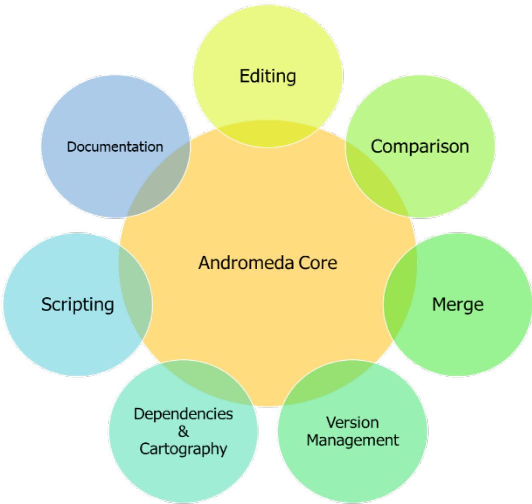

Figure 4: Modules of Andromeda

Screenshot from Andromeda main graphical user interface (GUI) from the METIS study case, /METIS 2025b/ is presented at Figure 5.

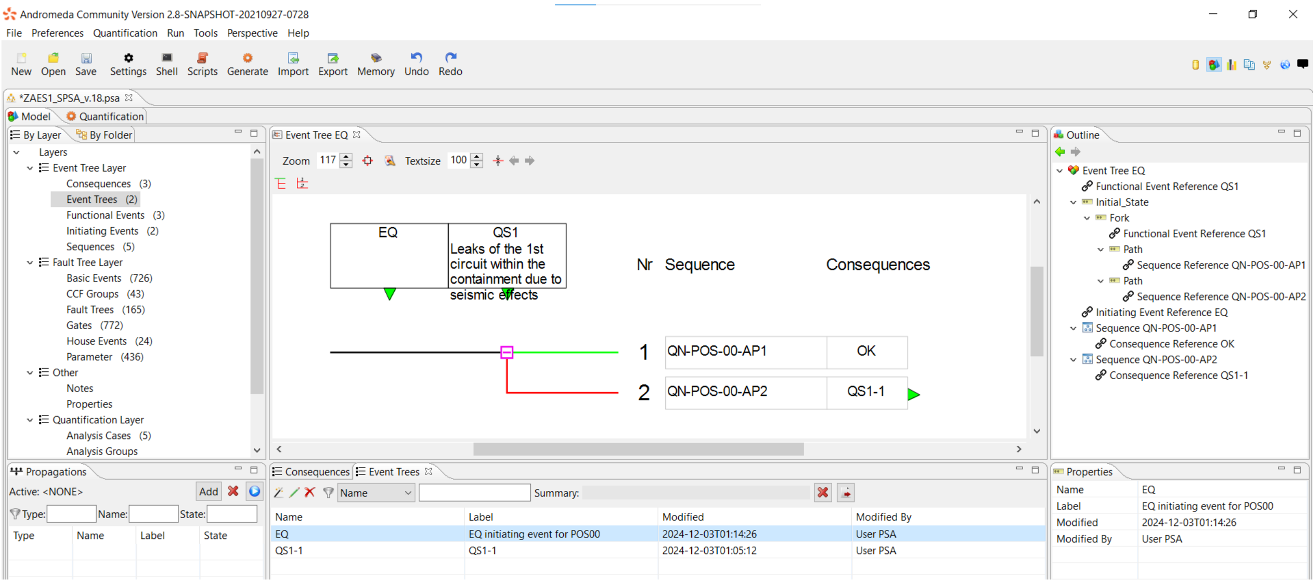

Figure 5 GUI of Andromeda

Two approaches are considered for the implementation of the Seismic PSA needs in Andromeda:

- Specific approach with embedding seismic specific elements (or extending existing parts) into the PSA domain in order to obtain seismic modeling. Advantage of the approach is simplicity, while disadvantage is that the approach is not coherent with the Andromeda philosophy regarding modularity and extensibility.
- Generic approach deals with introducing generic elements into the existing Archetype Modeling Language (AML) modelling framework domain for PSA models. The generic elements could serve to represent seismic information by the means of generic expressions (that are themselves non seismic specific e.g. attributes), see Figure 5.

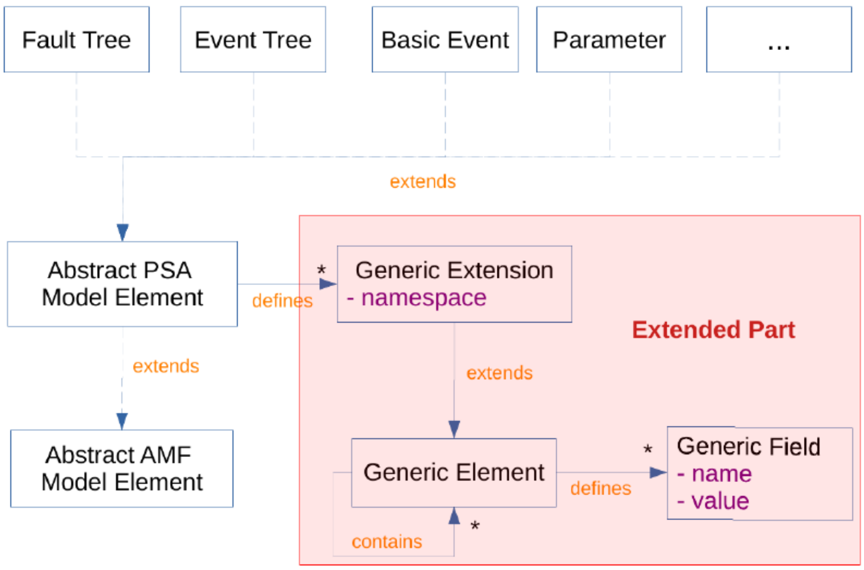

Figure 6. Generic extension of the PSA domain with seismic modeling

Within the context of the METIS project, Andromeda is coupled with the an open-source quantification software SCRAM.

1.2. SCRAM software

SCRAM is a Command-line Risk Analysis Multi-tool that can perform event tree analysis, static fault tree analysis, analysis with common cause failure models, probability calculations with importance analysis, uncertainty analysis with Monte Carlo simulations. SCRAM makes it possible to calculate the probability of failure of a safety mission at a time t (of a TOP Event), given the failure probabilities of the basic events depending on time, denoted Q(t). In other words, SCRAM makes it possible to calculate time-dependent unavailability of a safety system. The basic event failure models available in SCRAM are those commonly used:

- Repairable component (exponential distributions for failure and repair processes),
- Periodically tested component (exponential distribution for the failure process, constant fixed test interval, constant fixed repair time. Optional time to first test different than test interval),
- Probability – Constant unavailability (Failure probability per demand),
- Fixed mission-time component,
- Non-repairable component (exponential distribution),
- Weibull distribution (exponential distribution with scale and shape factors),
- User defined.

The calculation of the mean unavailability of basic events within PSA model is possible using user-defined probability of unavailability. Under Andromeda, it is possible to use different models for the Basic Events (REPARAIBLE, TESTED, FIXED, MISSION-TIME). For quantification of minimal cutsets (MCS) by SCRAM different algorithms can be used (exact probability calculation with binary decision diagram based algorithms, rare event approximation, min-cut upper bound).

In the METIS tool, SCRAM is dedicated for quantification of PSA results. Under METIS project, initial version of SCRAM was modified to make it usable and compilable (available at https://github.com/SCRAM-NG/scram/releases/download/0.17.0/scram_ng_0.17.0.zip). New version, SCRAM-NG (next generation) is described in /METIS 2023b/.

Quantification flow using coupled Andromeda-SCRAM is illustrated in Figure 6

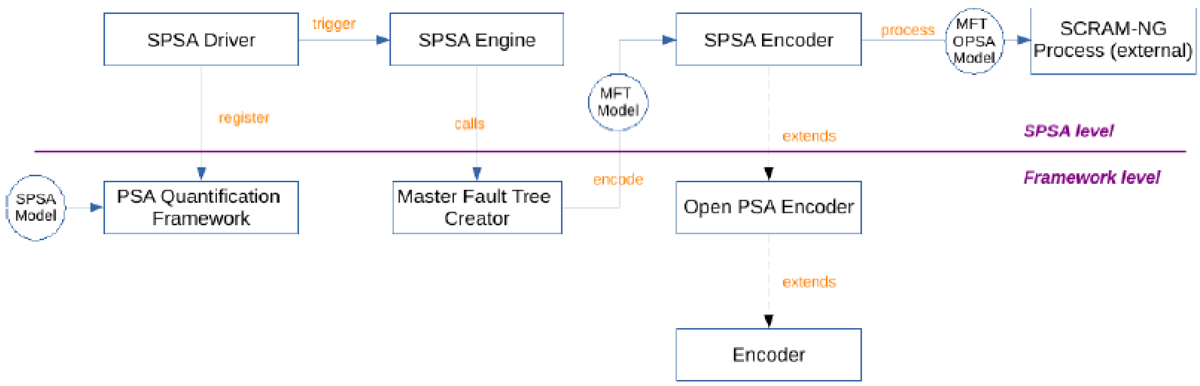

Figure 7 Overview of the main steps of the quantification pipeline of SPSA models, /METIS 2022/

1.3. Seismic Data Base tool

For calculation of SSC failure probability, a stand-alone tool, the Seismic Data Base (SDB) tool was developed under the METIS project, (see Figure 4). SDB tool allows to express the relation through mathematical laws between the SSC failure probability and upstream parameters used in these laws (like PGA level for example). The following features of the SDB tool can be highlighted:

- EPRI method for fragility analysis is implemented;
- Correlation due to common parameters;
- Module for MCS set re-quantification (rare event approximation).

This SDB is designed to be flexible (possibility to define new mathematical laws), simple and robust (internal check of data consistency). It can be used either to generate the probability of failure of each SSC for a given seismic hazard level (in the frame of a seismic PSA approach with several discrete intervals defined by the analyst); or to generate a sampled set of SSC seismic failure probability (Monte Carlo approach) for a given seismic level or for the entire spectrum of seismic levels in a continuous manner. The principle of this tool is to allow the user to declare all the parameters used to fit the different mathematical laws that define the seismically induced probability of each basic event of the seismic PSA. These parameters are named "parent" or "upstream" parameters and can be shared by several basic event probability definitions. Each upstream parameter can be: a fixed value; a random and independent value (defined by a distribution law); a value based on upstream parameters (i.e. defined from "grandparents" parameters through mathematical laws), //METIS 2023c/.

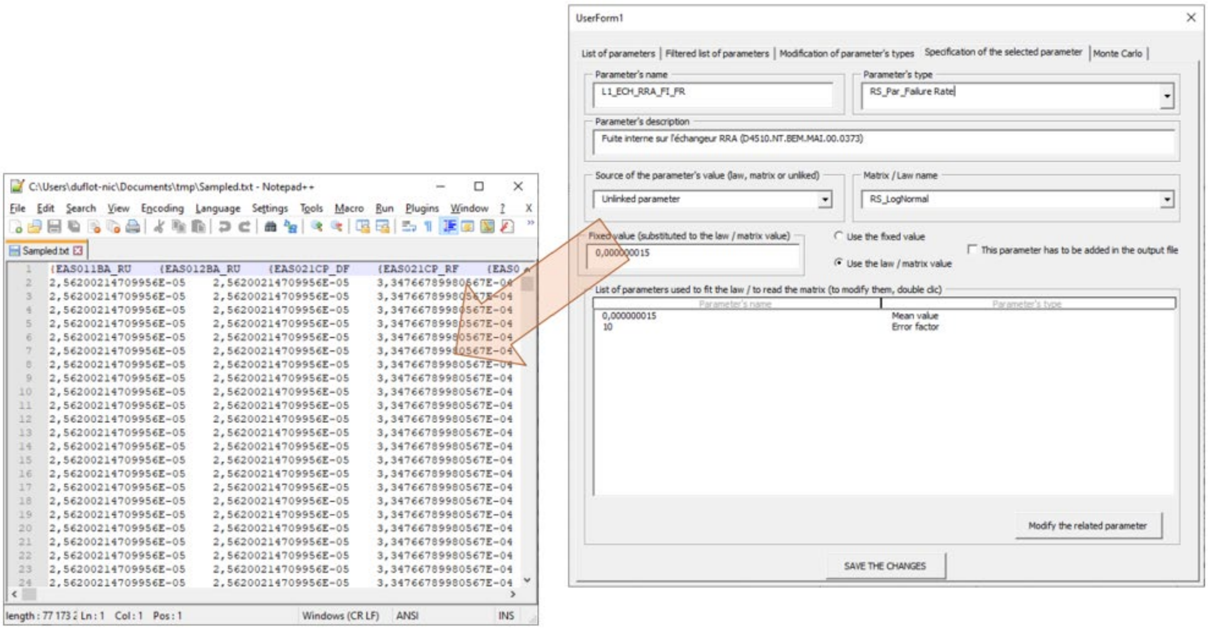

Figure 8 GUI of the SDB tool

The tool also have password protected developer mode to be possible to introduce new mathematical laws (equations) to define needed parameter's values. These laws can be defined based on:

- their name (which must be unique),
- their description,
- the number of parameters used to fit them,
- the formula used to define the law. This formula has to refers only to the cells located on its right at the same line: i.e. to the fitting parameters list. Any combination of mathematical laws implemented in Excel can be used.

The tool has been reviewed and tested by the task partners, revealed bugs (if any) have been resolved.

1.4. Uncertainty propagation tool

In addition, a module that, given the samples of basic events probabilities (resulted of uncertainty propagation) and given the results of the Seismic PSA model in terms of MCSs, is able to provide the value of the risk metric for each sample has been developed. The user generates: file from Andromeda-SCRAM, containing the cutsets, file from SDB tool containing the sampling values for basic events. Then, the user precises these files as inputs by using the graphical interface of the tool (see Figure 5), together with the path and name of the folder.

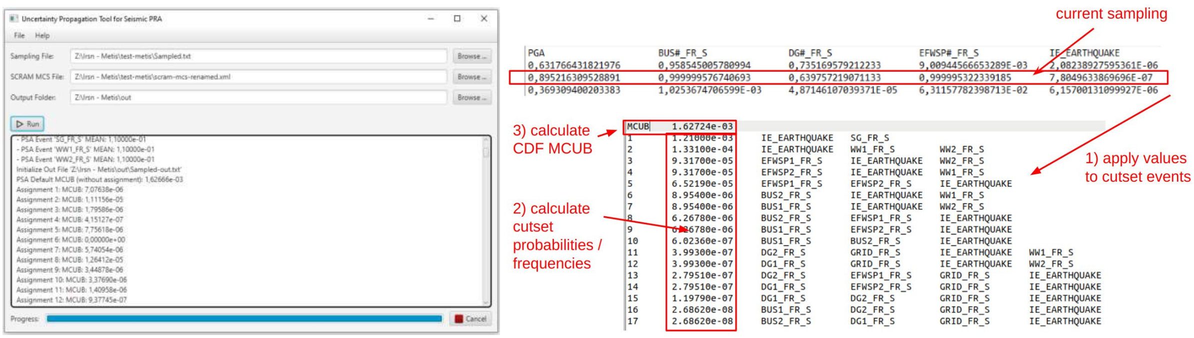

Figure 9 GUI of uncertainty propagation tool

The tool generates a file similar to the original sampling file but with an additional MCUB column containing the calculated CDF values. At each iteration, basic event values from the current sample are applied (1) in order to re-calculate MCS values (2) and the final CDF value (3), see Figure 5.

1.5. Benchmark

In frame of METIS project representative benchmark calculations were performed for the METIS tool developed in framework of WP7, using proven PSA commercial codes.

The scope of activity included:

- Selection of representative hazard scenario(s);
- Model testing and benchmark calculations using the METIS tool vs commercial PSA tools.
- Development of recommendations for improvement of the METIS tool, based on benchmark results and test calculations.

This study has been performed using the following codes and software:

- SAPHIRE version 8.1.8;
- RiskSpectrum PSA version 1.4.0;
- METIS tool (coupled Andromeda-SCRAM, Seismic database tool).

The benchmark calculations were conducted for two scenarios. In these simple scenarios, it is supposed that the seismic event, whatever its PGA, induces a reactor trip and a switch from the main feedwater to the emergency feedwater with a probability of one. Such a modelling is of course a conservative simplification since low-PGA seismic events would not trigger any reactor trip or loss of the main feedwater and would therefore not require the successful operation of the emergency feedwater for preventing core damage. In a more realistic seismic PSA study, one would have to introduce a probability for each level of PGA of the seismic event to trigger a reactor trip and a switch from the main feedwater to the emergency feedwater. The main differences of these scenarios (benchmark cases) are in different seismic input data and component fragility data. As additional difference of the scenarios is the consideration of national grid power. Selection of these scenarios was made in order to investigate the impact of the different seismic input data used on the benchmark results and to obtain validation results for a wider range of seismic impacts.

The benchmark results showed good agreement between METIS tool, SAPHIRE and RiskSpectrum, that could conclude, that using of the similar input data and similar approaches for modelling could establish evidenced results of the METIS tool.

For analysis of the differences between SAPHIRE/RiskSpectrum and METIS tool calculations, the additional study was performed. Results of this study showed, that if the failure probability for components calculated by code using seismic parameters (Am, βu and βr), it produce more accurate calculational results.

2. Considered approaches

2.1. Strategy for consideration of aftershocks in seismic PSA

Nuclear power plants are complex and critical structures comprised of numerous interdependent structures, systems and components, whose safety must be rigorously evaluated through probabilistic safety assessment. During the time between a reactor's emergency shutdown resulting from a mainshock and its subsequent cold shutdown state, some SSCs may experience nonlinear behavior due to the mainshock, but they do not fail. The importance of aftershocks lies in their potential to compound the effects of the mainshock, potentially leading to the failure of these SSCs. In addition, the core damage sequences that were in progress because of the mainshock can be exacerbated by additional failures (e.g., containment functions) due to aftershocks. On the other hand, due to automatic shutdown for significant events, it is expected that the plant vulnerability decreases, that is robustness increases when an aftershock occurs. However, the occurrence of an aftershock during this time frame may affect the NPP safety based on the cumulative damage of both the mainshock and aftershock, which can result in the failure of these SSCs. Analyzing these failures, understanding the accident sequences that they contribute to, understanding how the associated risks can be reduced, and developing other associated insights are the principal tasks of an aftershock seismic PSA analysis.

Several challenges were identified associated with treatment of aftershocks, like:

1. Identification of the post-mainshock plant state, status of each of the critical safety functions, and timeframe of importance for aftershocks consideration;
2. Characterization of the damage state of the plant and SSCs important to safety after the mainshock;
3. Lack of data to characterize fragilities of SSCs that have suffered partial damage from the mainshock;

4. Characterization of the aftershocks hazard (conditional probability and/or probabilistic hazard characterization as a function of the "size" of the mainshock);
5. It is necessary to consider both sequences that do not result in a core damage state after the mainshock analysis but have some damage and accident sequences that result in a specified core damage state and are vulnerable to further damage from the aftershocks;
6. Understanding the usefulness of modifications made in response to the Fukushima event (e.g., FLEX equipment and offsite resources).

To cope with these challenges, a strategy for consideration of aftershocks in seismic PSA was developed and tested by PSA calculations.

The general method for consideration of aftershocks in Seismic PSA includes the same main stages, as for mainshock PSA:

- Seismic hazard analysis of aftershocks: aftershock activity can be predicted by combining the estimate of the number of aftershocks after the mainshock and the frequency of aftershocks of certain magnitude. Seismic motions caused by the aftershocks are estimated from the attenuation equation or fault model, taking into account the spatial distribution of aftershocks in the source area.
- Seismic fragility assessment: the fragility of SSCs can be estimated by considering seismic vibrations caused by the mainshock and aftershocks that can occur within a short period of time.
- Analysis of systems: reliability analysis of NPP systems taking into account additional impacts (failures) caused by aftershocks while the reactor plant is in cold shutdown state after the emergency shutdown resulting from the mainshock.

To assess the seismic hazard of aftershocks, a model was developed for stochastic prediction of aftershock activity. Aftershocks are assumed to follow a truncated Gutenberg-Richter distribution /Felzer, Abercrombie, and Ekstrom 2004/, where the total number of earthquakes N above some magnitude M is quantified as

$$N = 10^{a-bM}. \qquad (1)$$

N is a function of the mainshock magnitude M_{main}:

$$N(M_{main}) = c10^{\alpha M_{main}} \qquad (2)$$

where α = 1.0 and $c \approx 0.02$, based on the global analysis by /Felzer, Abercrombie, and Ekstrom 2004/. c is a scalar aftershock productivity parameter, while α controls the scaling with mainshock magnitude.

The a, b, and M_{max} parameters for the truncated Gutenberg-Richter distribution must be defined as well. The b parameter is calibrated based on observed seismicity, jointly with c. M_{max} is more challenging to determine from seismicity data, as it is necessarily tied to the declustering process (during the construction of the seismic catalogue used in the development of the mainshock PSHA model) and explicit choices about whether a smaller event shortly before a larger event is a foreshock or whether it is a mainshock with a larger aftershock. To be clear, this classification does not come from the data but is an explicit and somewhat semantic decision made by the modeler. Nonetheless, there are two obvious choices for the aftershock M_{max} parameter: it may be the regional mainshock M_{max} (in which case it will be as large or larger than any given mainshock), or it may be related to the mainshock magnitude, for example equal to that magnitude (or perhaps smaller by a delta, as following Båth's law). The a parameter is calculated algebraically by relating Eq. 1 and Eq. 2.

The first step in the process of calculating the aftershock occurrence rates is to estimate the aftershock productivity parameters. This step should come after the seismic catalogue has been declustered, and requires the association of aftershocks removed in the declustering process with the causative mainshock. This association is not always part of the declustering procedure, depending on the methods used, so additional post-declustering analysis of the mainshock and aftershock catalogues may be necessary.

We use a nonlinear Monte Carlo inversion for the aftershock productivity parameters *b* and *c*, defined in Eq. 1 and Eq. 2, respectively.

First ranges are defined for *b* and *c*, and then some large number of samples is drawn from uniform distributions based on those ranges. Each sample value of *b* is paired with a sample value of *c*.

For each (*b, c*) pair, we iterate over all of the mainshock-aftershock clusters from the observed seismic catalogue and calculate the likelihood of observing the empirical magnitude-frequency distribution of the cluster given the truncated Gutenberg-Richter distribution for the values of M_{main}, b, and c considering the year of the mainshock and the catalogue completeness for that year. The total likelihood of each (*b, c*) pair is the geometric mean of the (*b, c*) pair likelihoods for each mainshock cluster.

This method produces a distribution of likelihoods, so that the single best (most likely) estimate for (*b, c*) can be chosen, or numerous values can be sampled proportional to their likelihood (i.e., Bayesian sampling) in order to incorporate epistemic uncertainties into the aftershock production rates.

Currently, the aftershock productivity parameter estimation methods are not implemented directly into the OpenQuake Engine or Model Building Toolkit, but simply in a standalone Python script.

After the magnitude-frequency distribution for each mainshock has been defined, all the ruptures within some distance (e.g., four times the mainshock rupture length) of the mainshock are selected for consideration as aftershocks.

The conditional occurrence probabilities for each aftershock rupture, given the mainshock rupture, are calculated based on the aftershock magnitude-frequency distribution and the set of ruptures within the distance threshold. The criteria involved in this determination are the distances from the mainshock rupture to each aftershock rupture and the number of potential aftershock ruptures within each magnitude bin in the magnitude-frequency distribution.

For each aftershock rupture, an un-normalized conditional rupture probability $p'(rup_i|main)$ is defined based on the distance d_i from the mainshock rupture to the i^{th} aftershock rupture (accounting for the finite geometries of each), so that the probability decreases exponentially with distance: $p'(rup_i|main) = e^{d_i}$

This probability is then normalized by the number of expected aftershocks in that magnitude bin $N(M_{aft})$ as derived from Eq. 2, and the sum of the un-normalized probabilities for all ruptures in the magnitude bin,

$$p(rup_i|main) = p'(rup_i|main) \cdot \frac{N(M_{aft})}{\sum p'(rup)} \qquad (3)$$

such that the sum of the normalized rupture probabilities is equal to $N(M_{aft})$.

Finally, the unconditional occurrence rate $r(rup_i)$ of some aftershock rupture i is calculated as the conditional occurrence probability times the occurrence rate of the mainshock:

$$r(rup_i) = p(rup_i|main) \cdot r(main)\,.$$

The total aftershock occurrence rates for each rupture, considering all mainshocks, is simply the sum of the $r(rup_i)$ values for every mainshock in the model (or any mainshock above a threshold value for generating aftershocks). These rates are added to the occurrence rate of each mainshock before the classical PSHA computation is performed. This model is however not suitable for developing seismic aftershock PRA and not usable in the framework of the approach proposed here.

The methods developed here for classical PSHA with aftershocks need to be modified or extended to support the creation of stochastic event sets for single mainshock-aftershock sequences or for model-wide sequences. For this purpose, the calibration of the time-decay parameter of aftershock generation (which is not necessary for the time-independent classical method) is needed.

For any mainshock taken from the seismic source model, the code is in place to calculate the conditional earthquake occurrence probabilities for each potential aftershock ($p(rup_i|main)$ from Eq. 3).

If a specific mainshock rupture is selected, for example, for a single event-based seismic hazard and/or risk analysis, then the set of potential ruptures can be selected and the $p(rup_i|main)$ values for all ruptures can be calculated. Then, a temporal sequence can be constructed by modifying the $p(rup_i|main)$ values based on the time since the mainshock. Finally, stochastic sampling based on the final probabilities can be easily performed through standard methods.

If a model–wide stochastic event set including aftershocks is desired, then first a mainshock stochastic event set can be created from the seismic source model using existing tools in the OpenQuake Engine. Then, for each of those mainshocks, the aftershock sequences can be created as described in the previous paragraph.

The seismic fragility of SSCs is evaluated using the assumption that seismic vibrations from the mainshock and aftershocks occur within a short period of time. The combination of the mainshock and aftershocks with strong impact on NPP is selected from the combinations of the mainshock and aftershock models.

Seismic responses of NPP SSCs are calculated using the combination of mainshock + aftershock impacts, and fragility curves are estimated as a conditional failure frequency for a set level of input ground motions. The SSC response analysis models are the same as those used in the analysis considering only the mainshock.

To consider aftershock by conditional distributions (scenario-based analysis), conditional fragility curves need to be developed. An empirical correlation model can be used to generate aftershock spectra conditioned on different mainshock records.

In order to develop a methodology for the derivation of the damage-dependent fragility curves, which account for clustered seismicity and are suitable for use in the context of PSA, two approaches have been proposed by the Strategy developers: a damage state dependent approach and a simplified shift-based approach.

For fragility calculations, the aftershock fragility needs to consider the damaged state from the mainshock, and the systems model should reflect the post-mainshock plant shutdown state.

Damage state dependent methodology consists of three steps. Firstly, for each mainshock ground motion, a compatible aftershock sequence is generated from the causative parameters of the mainshock event using the Epidemic-Type Aftershock Sequence (ETAS) model. Secondly, from the knowledge of the causative parameters of the selected aftershock, the response spectrum of the mainshock ground motion and the empirical variance-covariance matrix of the spectral accelerations of historical mainshock (MS) and aftershock (AS) ground motions recorded at the same station, the expected (target) MS-consistent AS response spectra are derived. Thirdly, this exercise will be repeated for many MS events and a DB of pairs of MS ground motion records and MS-consistent AS ground motion records will be assembled. This DB of ground motion pairs will be used to create fragility curves that depend on the damage state of the structure after the MS event.

For implementing this methodology, definition of different damage states (DS) for every SSC is needed. So, a fragility curve will be developed for every DS of every SSCs based on the selected MS–AS sequence suite.

Figure 10 shows the damage dependent fragility functions obtained for a RC-ESDOF system through the above procedure. For the derivation of damage state-dependent fragility curves, up to four distinct DSs were considered with thresholds estimated from the yield and ultimate displacement capacity of the ESDOF system. The spectral displacement responses, obtained from subjecting the oscillators to each record of the selected the MS–AS sequences, were grouped together on the basis of the initial DS of the oscillator prior to the analysis. Fragility functions were then fit through maximum likelihood estimation for each initial damage state.

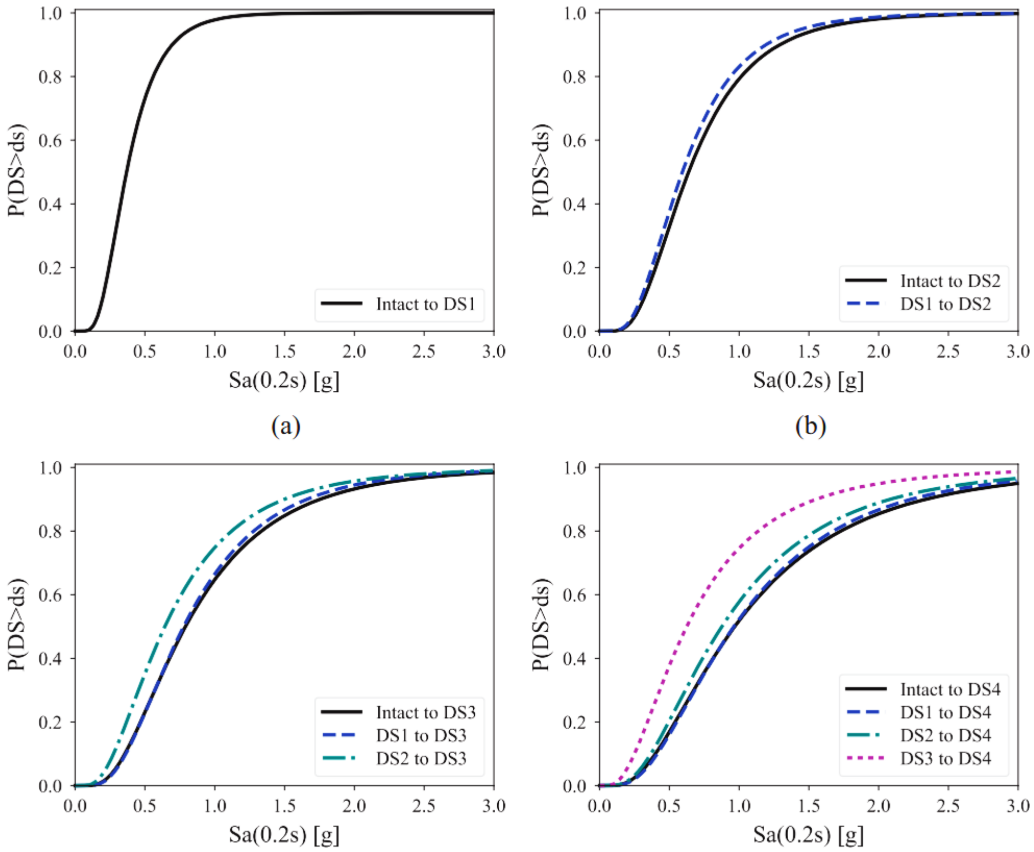

Figure 10: Damage-dependent fragility model for a RC-ESDOF system

The shift-based approach focuses on the changes in the fragility curve due to the additional damage of the mainshock. Since it is not dependent on the damage states and specific record selection of fragility calculation approaches, it offers a fast and simple prediction of the aftershock influence on the seismic fragility. The calculation of a simple shift in the curve, similar to a seismic margin, allows a simple integration in the current analysis approaches for NPPs. The procedure is illustrated in Figure 11.

The shift-based approach is based on the fact that the fragility curve of aftershock will shift to the left side of the fragility curve of mainshock because of structural damage due to the mainshock and lower intensity. The shift factor is calculated as a function of the mainshock damage to the intensity ratio:

$$\text{Shift} = F\ (\text{Mainshock Damage/Intensity e.g., PGA})$$

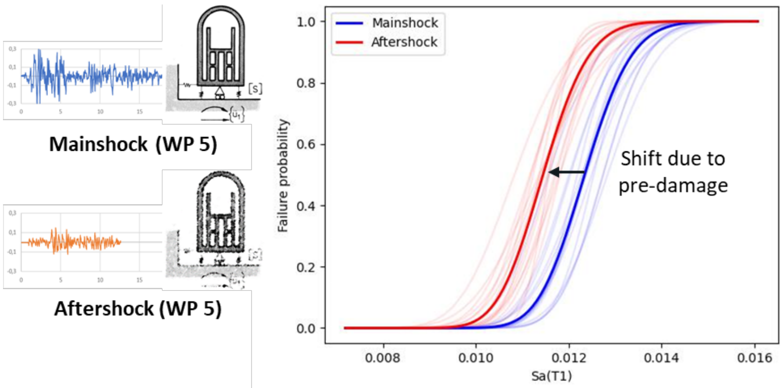

Figure 11: Shift-based approach for the quantification of aftershock impact on seismic fragilities

It should be note that developing the conditional fragility curves is a very complex task considering a lot of uncertainties that have to be analysed and considered. Future research into these areas would be necessary.

Probabilistic part of PSA for aftershocks includes modification of mainshock PSA models (both fault trees and event trees) to account predicted condition of NPP after mainshock (time frame between mainshock and aftershock) and to model additional failures of those SSCs that have survived mainshock. It was recommended to consider in the aftershocks PSA those initiating events that have occurred in the period from the reactor emergency shutdown caused by the mainshock to the transition to cold shutdown state, as shown in Figure 6. This duration can vary depending on the design of NPP (PWR, VVER) and on plant-specific operational procedures. Duration of associated plant operational states (POS), as well as list of operable SSCs needed to achieve long-term safe shutdown states are determined/modeled at Low power and shutdown modes PSA. That is why for aftershocks PSA a full-scope PSA model that covers all POSs is needed.

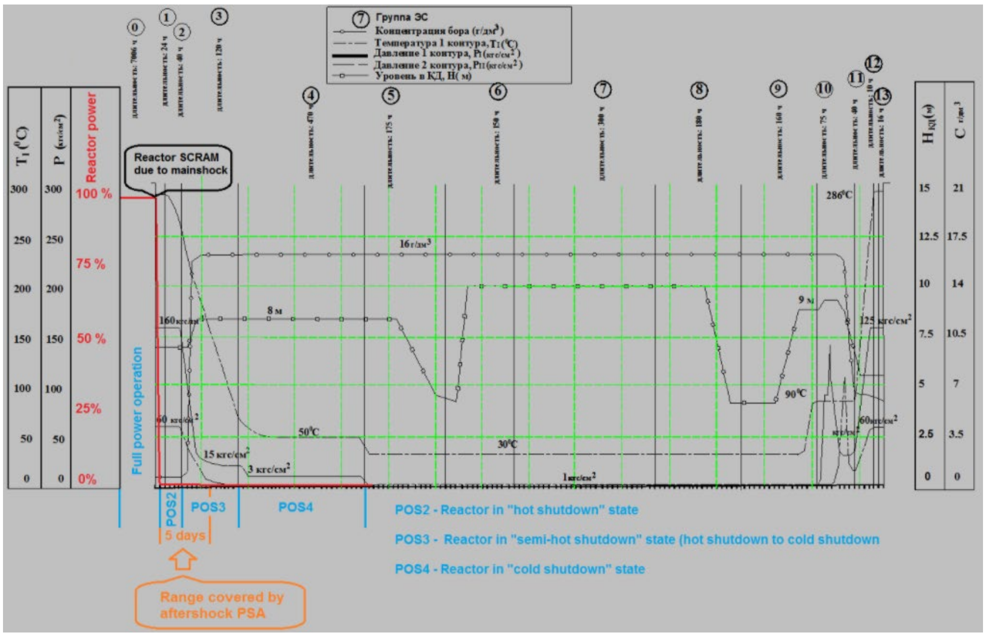

Figure 12 Relation of mainshock and aftershocks with plant operational states (ZNPP example)

In Seimic PSA, for each level of seismic impacts, an event tree is developed to define the hierarchy of initiating events that may be caused by this particular impact, depending on their effect on the NPP. To assess aftershocks in accident sequences, success paths leading to cold shutdown have to be selected, excluding fault paths to be considered as core damage from the mainshock (see Figure 7). The event trees for aftershocks are modeled in the same way as for the mainshock, taking into account the POS.

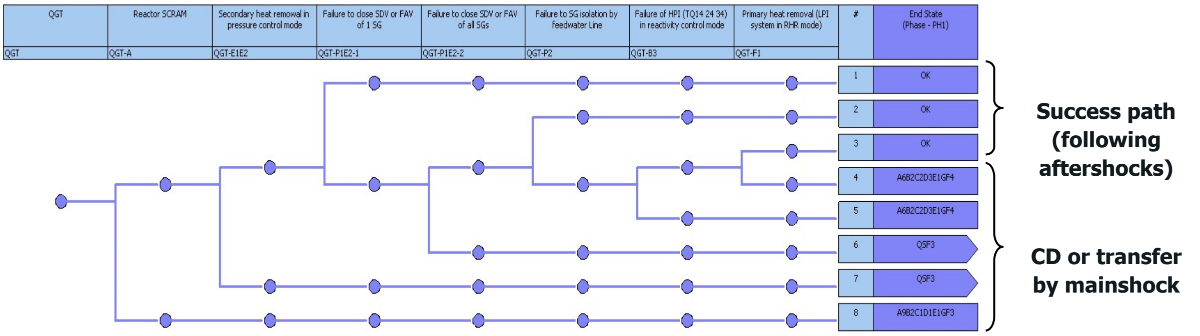

Figure 13: Example of a general transient event tree

The fault trees should be modified: for each SSC that is presented in the model, potential failure caused by a random failure (defined in the component reliability database) and potential equipment failure caused by a seismic impact from the mainshock and aftershocks should be considered. SSC failure caused by an aftershock is modeled explicitly in the fault trees. The probability of failure caused by an aftershock is estimated by multiplying the probability of zero failure (non-failure) of the SSC from the mainshock and the probability of its failure from the aftershocks: Pas=(1-Pms)*Pas, see Figure 14.

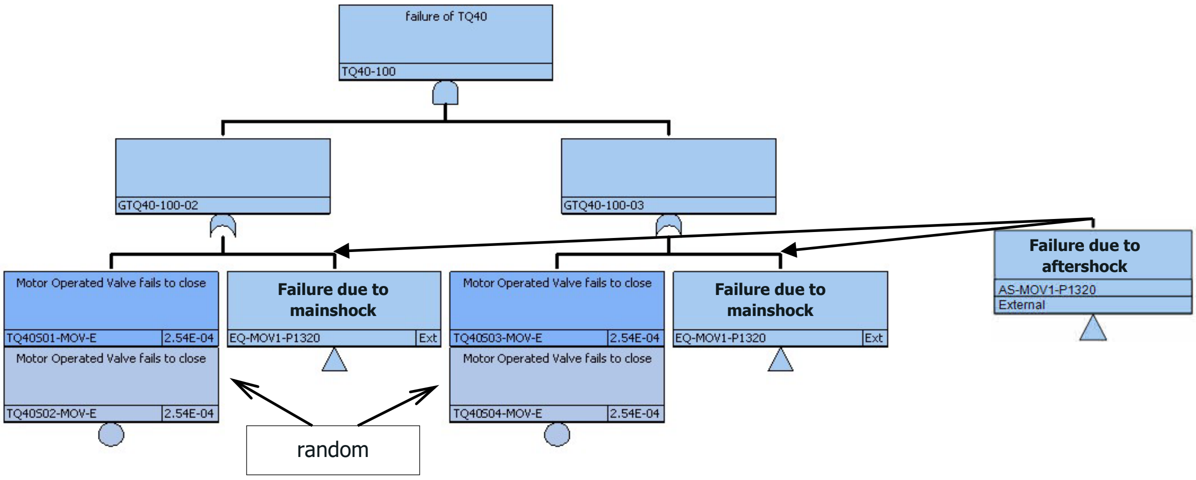

Figure 14: Example of considering aftershocks in the fault tree

Actually, the total risk contribution is quantified using a simplified formula:

$$CDF = \sum_{i=1}^{n}[Hm_i.CDPm_i] + \sum_{i=1}^{n}\left\{(1-CDPm_i)\sum_{j=1}^{k}[Ha_j CDPa_j]\right\}.$$

The time frame over which aftershocks are to be considered and the number of aftershocks are important and need to be discussed. In our view, the analysis does not need to consider multiple aftershocks.

2.2. Seismic correlations

Earthquakes, particularly large ones, are a significant source of common-cause failures in systems, structures, and components. They can impact all components and systems of NPP, as well as all facilities and radiation sources at an NPP site. As a result, earthquakes can lead to the simultaneous failure of multiple redundant safety systems. It is important to identify and account for the dependencies between seismic events and SSC failures, as addressing these dependencies can significantly influence both the qualitative and quantitative results of a seismic PSA.

In a single-unit PSA, correlation—similar to common-cause failures—becomes important when there is a high degree of redundancy relative to the success criteria. For instance, in a three-train safety system where only one train is required to mitigate an accident, it may be necessary to assess the impact of correlation. For multi-unit PSA, evaluating correlated failures becomes even more complex, requiring a more detailed approach to accurately assess the risks.

In a seismic PSA, the component failures represented in a minimal cut set may be correlated through their respective responses and fragilities (correlation between component fragilities). Sources of correlation may be:

- seismic intensity variability correlation;
- soil and structure amplification correlation;
- component capacity correlation.

Term correlation used in the METIS project means dependency of failures of SSCs having similar design and plant location that are affected by the same seismic load. Seismic dependency can be defined in terms of the joint probability of two or more seismic caused failures, conditional on the occurrence of an earthquake.

Generally, probabilistic model can contain different failures of SSCs: random failures, noncorrelated seismic failures, groups of correlated seismic failures. While guidelines for treatment of random failures are well matured, approaches for consideration of correlated failures are still under discussion. This is associated with complexity of identifying correlation groups and determining the correlation levels. There are several assumptions that can be adopted for modelling of seismic correlations between SSCs failures:

- Full correlations;
- Zero correlations;
- Partial correlations.

The assumption of full correlations means that failure of one component implies the failure of all components in the group. Such approach is usually recommended for identical components (which are designed, manufactured, delivered, installed, tested, operated, maintained and stressed in parallel) in proximity that are mounted with similar anchorage. Typically, many seismic PSAs, for the sake of simplicity or due to insufficient data regarding correlations or due to limited resources, adopt full correlations approach for such SSCs. In practice, during development of probabilistic models, seismic failures of all identical SSC or all components in a fragility group are modelled as one basic event in a fault tree. Clearly, using full correlation approach is simplified and usually conservative. In some cases, it might be excessively conservative.

Assuming full correlation between SSCs is conservative in cases where the components are in parallel on the success path – so instead of multiplication of several SSC failure probabilities (using AND gate), one failure probability is applied. When the components are in series on the success path, full correlation is not conservative. In this case one failure probability is applied instead of sum of several SSC failure probabilities (using OR gate). Therefore, such aspects should be accounted for during selection of modelling approach for correlated failures.

As opposite to full correlation approach, the assumption of zero correlations or full independence may be appropriate for non-identical SSCs. Clearly, using zero correlation approach for all SSCs (including similar ones) can be sometimes non-conservative.

Dependency among seismic failures in a practical PSA tends to be treated in an approximate manner due to difficulty in calculating combination probabilities of correlated seismic failures, which results from difficulty in determining correlation groups and correlation level. Traditionally, strongly correlated failures can be idealized as one failure and weakly correlated failures are idealized as independent in the logic tree. So, the almost universal practice among seismic PSA practitioners has been to use binary approach - only full or zero response correlation. The current practice for treating seismic correlation in a seismic PSA is to screen out seismically rugged components (for screening recommendations see /METIS 2021b/) and then develop correlation groups for the screened-in components to represent the simultaneous failure of similar components during an earthquake. If components are similar in design, with similar anchorage, and located in the same building and elevation, then their failures are treated as fully correlated failures. Otherwise, it is assumed that there is no correlation among component failures, and failures of similar components in different buildings are not correlated. Consideration of partial correlations is needed to avoid excessive conservatisms / non-conservatisms inherent to binary (full/zero dependency) approach, and to obtain more realistic, more meaningful results of seismic PSA.

The process and approaches for consideration correlations in seismic PSA have been proposed in /METIS 2024/, see Figure 12.

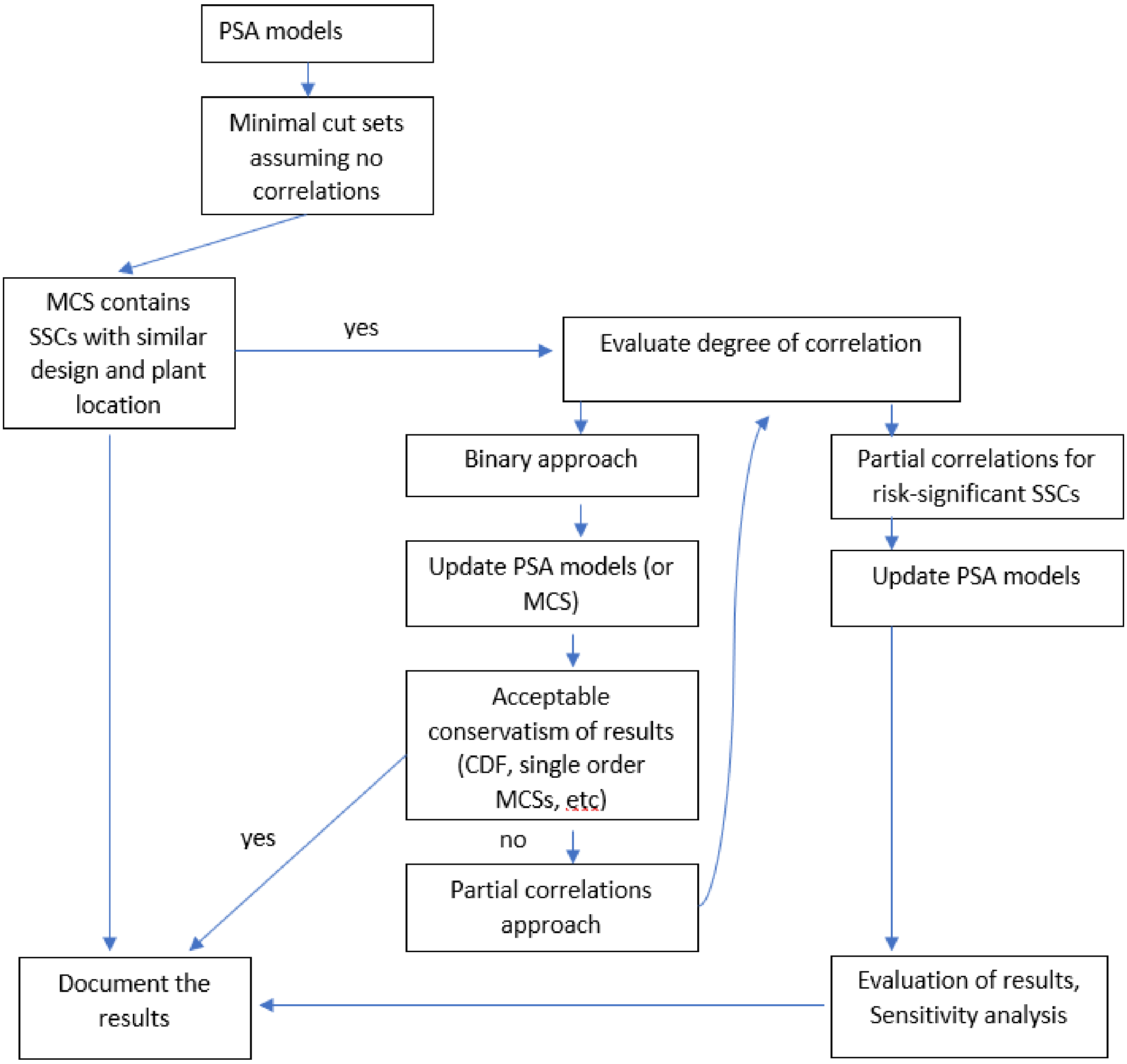

Figure 15 Consideration of correlations in seismic PSA

Based on evaluation of international experience, the general rules for assigning correlation coefficients depending on the following factors have been summarized in /METIS 2024/:

- SSC design;
- SSC location in buildings/floors;
- SSC orientation;
- SSC sensitivity to spectral acceleration.

Ways for incorporation of partial correlations into seismic PSA model were proposed, as well as beta-factor common cause failures (CCF) method was judged as appropriate for seismic PSA, in terms of understandability for PSA practitioners. This method was applied for the METIS study case components, relationships between beta-factor CCF (β) and correlation coefficients, (ρ) depending on different PGA levels were calculated, see example on Figure 13.

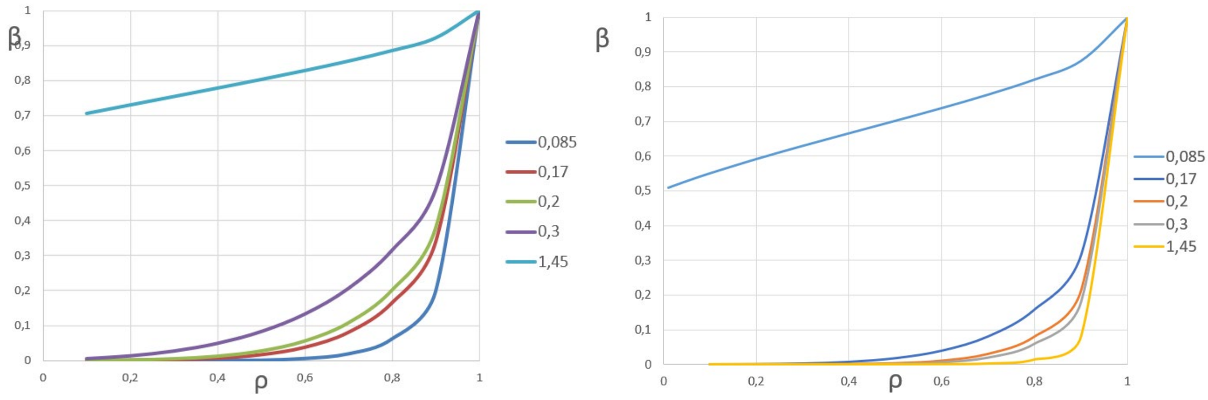

Figure 16: β-ρ curves for 0,4 kV busbars, for different PGAs. Left – 2 members in seismic correlation group, right – 3 members.

2.3. Seismic human reliability analysis

Human failure events (HFE) explicitly modelled in seismic PSA model need to be identified and reviewed. According to human reliability analysis (HRA) methodology three categories of human actions should be considered:

- Pre-initiator (type A) actions - human actions before the initiating event during normal operation that degrade system availability (e.g., mis-calibrations, misalignments). Such actions do not depend on the characteristics of the later initiating event, thus results of the analysis performed during the internal event PSA remain in effect for seismic PSA. It may be necessary, however, to model Type A actions to supplement for systems that are newly modelled for seismic events. Applied method can be the same as that used in the internal event PSA.
- Human induced initiating event (type B actions) - not applicable in the case of seismic initiating event
- Post-initiator (type C) actions. Discussion below deals with Type C human actions.

Existent HRA methods have been developed for different applications, mainly related to internal initiating events/ internal hazards. Standard HRA method used in the internal events PSA must be revised to address the effects of earthquakes on operator performance. Two approaches can be applied:

(1) A model in which seismic HEP is independent of the level of ground motion. Under this approach, HEPs for the same HFE for all seismic intervals would be the same. Seismic PSA study for ZNPP Unit 1 utilizes this approach, /ZNPP 2019/.

(2) A model in which HEP during an earthquake depends on the PGA.

A number of seismic related factors on human actions (seismic factors) were identified. Their impact on human error probabilities should be considered to obtain more realistic value of CDF. These factors include: mental and physiological stress induced by earthquake; additional workload (above that for similar sequences not caused by seismic events); uncertainties in event progression (e.g. cue availability, timing concerns, failure of signals, spurious signals, failure of communication systems); effect of seismic failures on mitigation and on response actions and recovery activities (e.g. accessibility restrictions, possibility of physical harm, equipment approachability - local operator actions might no longer be possible, manual action might not be possible due to failure of specific components); specific operator action aids and training (e.g. procedures, training exercises); increasing chance for errors of commission - human failure event resulting from a well-intended but inappropriate, overt action that, when taken, leads to a change in the plant and results in a degraded plant state (e.g. intentional isolation of the Isolation Condenser system at Fukushima Dai-ichi as per operation manual).

HRA approach which is consistent with another important aspect, SSC fragility analysis, was proposed and adjusted in /METIS 2024b/. It deals with HRA damage states. Depending on ground motion magnitude (and associated failures of SSCs), damage states for HRA are defined. The combinations of the environmental conditions and the types and number of SSC failures create a context for the operator actions modelled. These damage states differ from seismic hazard bins and are defined by grouping SSCs by their level of expected impact on human performance if they fail. Several levels of the probabilistic modelling of impact are possible: inability of action - depending on HDS, the plant staff has insufficient conditions for performing their task – directly accounted in fault trees/event trees; if the plant staff tasks are feasible, a probability of insufficient workplace conditions due to seismic damage (e.g., instrumentation is damaged and does not provide information to the operator) is modeled in fault trees; while indirect impact of seismic events is modeled through increasing HEP by consideration of associated performance shaping factors according to applied HRA method.

Reference PGA values and adjusted multipliers for HEP depending on the damage states, time margin for human actions, location of the action and availability of cues have been proposed.

The HRA approach was implemented for the METIS study case.

3. The METIS study case

The METIS study case was defined in WP3 and was modeled using the METIS tool in the framework of WP7. The case study is hybrid one. It deals with the combination of the Zaporizhzhia Nuclear Power Plant Unit 1 SSCs virtually placed to selected site in central Italy (for seismic hazard assessments). ZNPP Seismic PSA model including fragility analysis constitutes the reference information to evaluate the impact of all METIS developments and proposed improvements.

One seismically induced initiating event "Loss of coolant accident", associated safety functions and front-line systems needed to perform the safety functions, supporting and auxiliary SSCs, as well as associated human actions were modelled in detail via the METIS tool. Scope of the PSA model – seven hundred basic events with failures of SSCs and human failure events, dozens families of common cause failures, hundreds fault trees with system failures, etc – is illustrated on the METIS tool screenshot (Figure 13).

Regarding seismic events, ten seismic intervals starting from design basis earthquake (0-0,085g) up to 1,45g.

Discrete approach has been used: the frequency of seismic intervals was derived by discretising the site-specific seismic hazard curve according to the PGA. The impact of the seismic initiating event is considered by incorporating seismic failures of the SSCs, with failure probabilities determined according to the fragility analysis.

The results of the following METIS project activities were utilized as input data for the METIS study case:

- WP3 "Case study for implementation and application of METIS results" – selection of nuclear power plant site for the study case, see METIS deliverable 3.1, /METIS 2021a/;

- WP4 "Seismic Hazard" – hazard curves for selected intensity measures for the study case, METIS deliverable 4.6 /METIS 2023a/;
- WP6 "Beyond Design Assessments and Fragility Analysis" – seismic equipment list for the study case, see METIS deliverable 6.1 /METIS 2021b/, fragility computations for METIS case study structures and components, see METIS deliverable 6.8 /METIS 2025/.

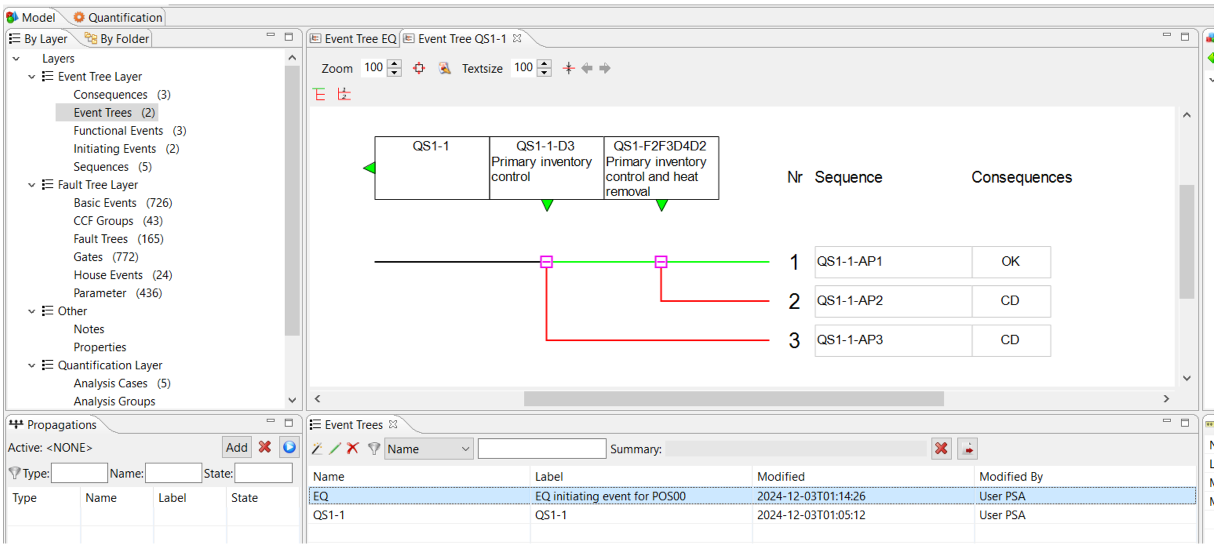

Figure 17 The METIS study case screenshot

For the METIS case study fragility computations were performed for limited number of risk-significant SSCs. For another SSCs, the appropriate information regarding seismic failure probabilities was taken from ZNPP Seismic PSA.

Actually, the case study has been intended to provide basis for comparison of different methodologies, and it does not represent a real PSA for a real NPP due to hybrid nature of the analysis.

The METIS case study includes approaches improved under the METIS project regarding treatment of seismic correlations, see Section 2.2, more precise modelling of seismic impact on human behaviour to ensure consistency with seismic fragilities of SSC, see Section 2.3. Human failure probabilities were adjusted depending on seismic level (PGA) and seismic influence on such performance shaping factors, like location of action, availability of alarm and control systems, time window, etc.

As part of development of the strategy for consideration of aftershocks in seismic PSA, separate probabilistic test calculations were fulfilled using the ZNPP base case model. The same seismically induced initiating event "Loss of coolant accident" occurred after mainshock with aftershock combination was modelled and quantified according to the proposed strategy.

The METIS study case model was developed taking into account the approaches and results prepared at the METIS project:

- new fragility parameters for risk-significant components;
- new human error probabilities;
- partial correlations for risk-significant redundant components, instead of full correlations;
- seismic levels that have been omitted in the reference PSA (between 0.3g and 1,47g).

The results – core damage frequency (CDF) and conditional core damage probability (CCDP) - are presented in Figure 15.

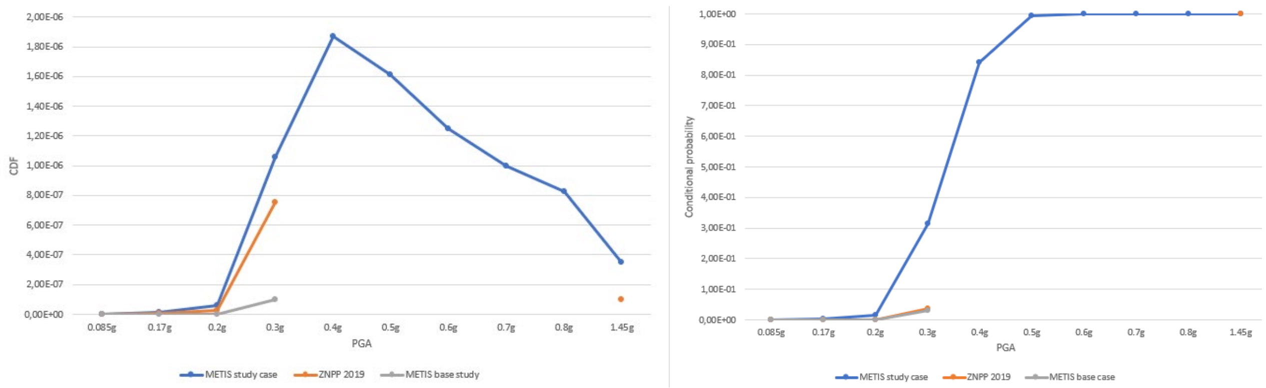

Figure 18: METIS study case CDF and CCDP

Shape of CCDP curve looks like fragility curve for a component, in some extent it can be called as "NPP fragility curve".

The results have shown significant, one order of magnitude increase in total CDF and CCDP comparing to base case, /ZNPP 2019/. This increase is totally explained by implementation of improved (approaches for SPSA.

Scope and order of dominant contributors have also completely changed due to new, more justifiable, fragility parameters for risk-significant components. For new risk-significant failures, like essential service water pump, control cabinets, partial correlations have been considered. According to the results of the sensitivity analysis, the CDF is not sensitive to the correlations of the base case dominant contributors (like diesel-generators, power supply components). The METIS study case re-evaluated fragilities have significantly reduced the importance of these components. From other hand, the CDF is more sensitive to the correlations between new dominant contributors, especially for medium range of seismic levels (0.17g, 0.2g, 0.3g). For higher PGA the CDF is not sensitive to any correlations due to dominant contributions of another SSCs like reactor building.

4. Discussion and recommendations

Based on the WP activities, the following can be recommended.

4.1. Seismic PSA aspects

4.1.1. Seismic equipment list

Structured approach for definition and classification of systems, structures and components, in order to perform generic fragility analysis or detailed specific fragility analysis was proposed, /METIS 2021b/. It includes the definition of process for identification of SSC, as well technical recommendations to develop seismic equipment list; qualitative and quantitative criteria to screen out SSC from further consideration (e.g., identification of inherently seismically rugged SSC and definition of low-significant SSC); quantitative criteria to decide which fragility analysis:

- Tier 1 - detailed plant specific study; or
- Tier 2 – generic analysis

should be performed for SSC.

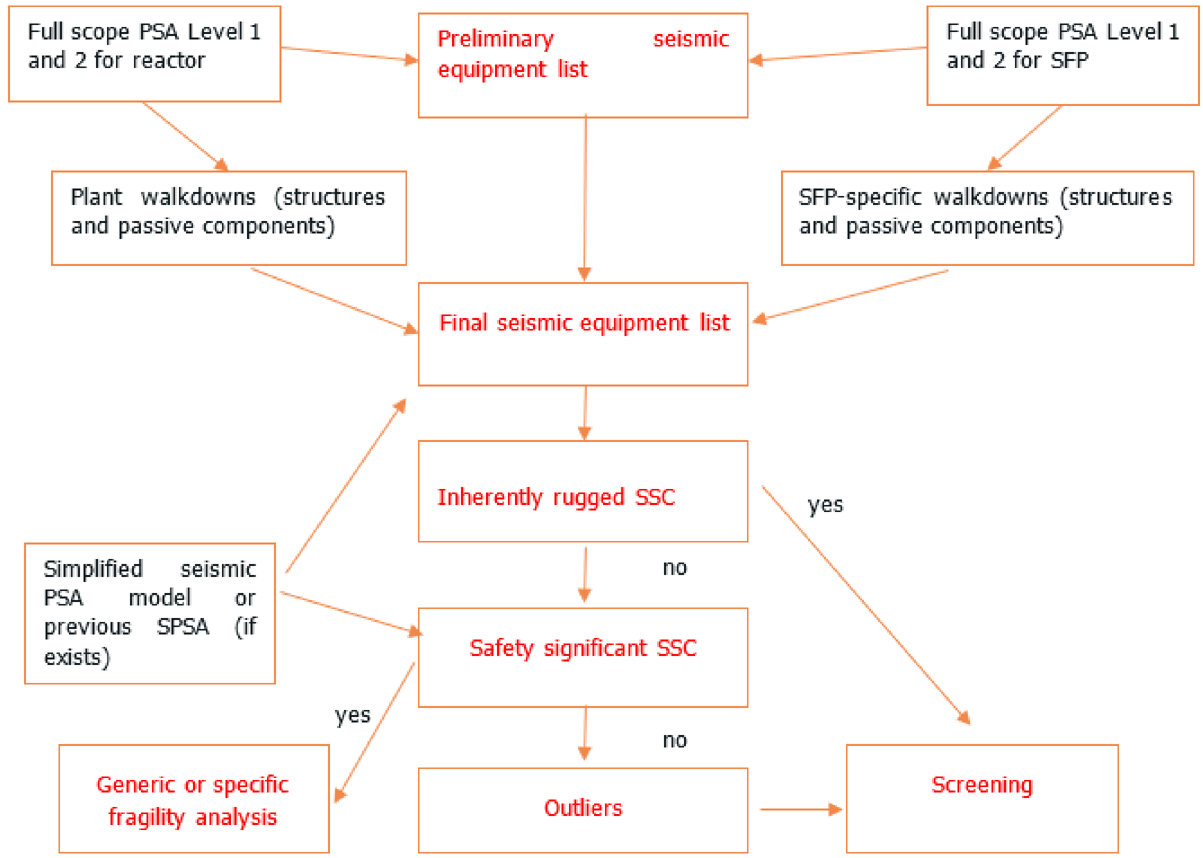

Figure 19. Definition of SSCs for fragility analysis

Criteria to define low-significant SSC and to distribute SSC between two types of fragility analysis were developed using risk-informed approach. It utilizes combination of different importance measures (Fussely-Vesely, risk achievement worth, Birnbaum) calculated at existent PSA for NPP in question (see Figure 17 for illustration).

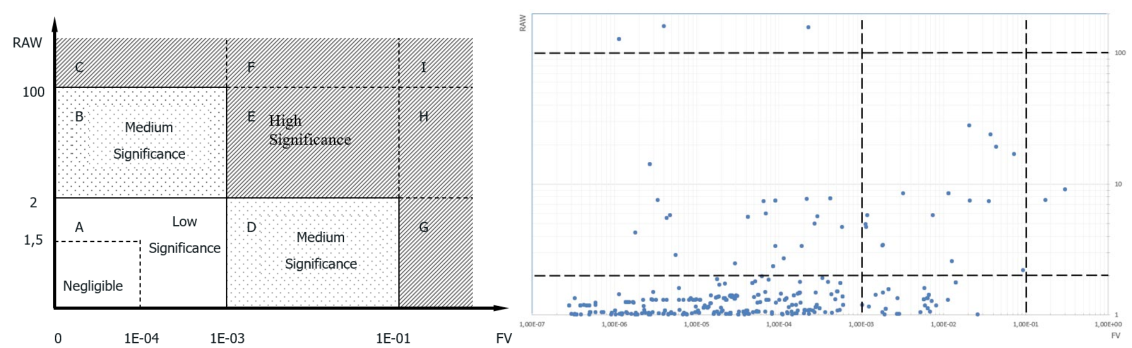

Figure 20: SSCs categorization criteria (left) and application for base case (ZNPP Unit 1, right)

Important aspects (as well limitations) that should be accounted for during development and adjustment of seismic equipment list (SEL) are also identified and discussed. The following should be highlighted:

- Truncation value. The truncation value applied for initial PSA /SPSA should be low enough so that the truncated set of minimal cut sets contains all the significant contributors and is low enough to cover at least 95% of the core/fuel damage frequency. Depending on the scope and level of detail of the PSA (modelling at component level vs subsystem/train level), the truncation value may vary from 1E-12 to 1E-8 per reactor year. The truncation value of 1E-12 was applied for the METIS study case;

- Completeness of PSA model. The initial PSA or seismic PSA model should comprehensively cover all significant operational modes of SSCs under analysis. It must include SSCs essential for fundamental safety functions in both the reactor and spent fuel pool across all plant operational states (nominal power, low power, and shutdown modes);

- Risk profile. An unbalanced risk profile occurs when the failure of a single SSC or a small number of SSCs disproportionately dominates the overall risk. Such an unbalanced risk profile means that the NPP does not have high level of defence in depth. In contrast, a well-balanced NPP risk profile distributes risk across multiple contributors. When risk is balanced (there are no disproportionally dominated SSCs failures), than importance measures, particularly Fussell-Vesely values, for the most SSCs will be low or very low. Care should be taken while screening out SSCs for NPPs with well-balanced risk profile. The SEL should contain SSCs contributing at least 95% to risk metric (CDF, FDF, LERF). Depending on the risk picture, in order to fulfil this rule, it may be appropriate to retain in the SEL all items with FV more than 1E-05;

- Uncertainties. Confidence in SSC ranking should not be significantly affected by data uncertainties. Sensitivity studies can help assess how SSC rankings change based on variations in reliability parameters;

- Common cause failures. SSC screening should account for both random failures and common cause failures. CCF probabilities can influence PSA results by either amplifying or downplaying component importance. Some SSCs may appear risk-significant primarily due to their role in CCFs, while others might be mistakenly deemed low-risk if their CCF contributions are minimal or absent

- Recovery actions. Recovery actions typically are modeled for dominant accident sequences, with their HEP depending on time window for cognition and execution time, as well as on other performance shaping factors like training, and procedures. Since success probabilities of recovery actions involve subjectivity, assigning high success probabilities may incorrectly rank related components as low-risk. Sensitivity analyses should evaluate how SSC importance measures change when recovery actions are excluded.

- As regard for screening by impact, system analysts establish a CDF screening threshold to exclude components not modeled in detail or replace them with surrogate elements. This involves setting a bounding fragility for SSCs, which, when convolved with the hazard curve, results in a failure frequency estimate. If the bounding fragility is well-chosen, SSCs with negligible risk contributions can be screened out. In seismic PSA, proper implementation of impact-based screening is resource-intensive and requires careful evaluation of failure modes, seismic correlation effects, and Level 2 PSA impacts. Setting a reasonable CDF screening threshold is also complex. Due to these challenges, this method is not recommended unless combined with seismic capacity-based screening;

- Use of Level 2 PSA importance measures may provide a different risk ranking of SSC fragility events. For example, failures of containment venting systems or mobile pumps may result in a LERF end states.

- When eliminating SSCs from consideration as risk-important using representative fragilities, care should be taken to understand why the SSC is less important. This should include an understanding of whether the contribution of the SSC will be controlled by the failure of other

SSCs, or if it is just the assumed representative fragility that is the basis. If it is just the assumed fragility that makes the SSC less important, this insight should be discussed with fragility experts.

- SSCs that have a significant uncertainty in the initial general fragility data and are satisfy Tier 1 criteria should be priority categorized for detailed fragility analysis. If there is significant uncertainty in the general fragility data, consider performing plant-specific fragilities for the SSCs that have the highest potential to impact the CDF/LERF.

In addition to SSCs directly included in the SEL, relay chatter must also be considered in the fragility analysis. During a seismic event, relay chatter can impact the functionality of components essential for bringing the reactor to a safe shutdown state. Seismically induced chatter may cause relays to send spurious signals to electrical and control devices, such as circuit breakers, motor starters, or other relays. This can lead to unintended equipment shutdowns or actuations. Beyond directly affecting SSC availability for safe shutdown, relay chatter can introduce additional risks, including:

- Operator confusion due to unexpected equipment behavior and misleading control panel indications.
- Initiating events, such as interfacing LOCA.

Relays whose chatter could negatively impact safety should be identified and further assessed. The impact of relay chatter on seismic risk can be significant for certain NPP designs. For instance, at the Krško NPP, relay chatter affecting core cooling and service water pumps resulted in an 8.1% change in CDF. However, some studies suggest that relay chatter is primarily a concern for older plants or has negligible effects on CDF in certain reactors.

The SEL categorization approach was applied for the METIS study case. 16 SSCs groups important to prevent core damage at reactor facility and 9 SSCs groups important to prevent fuel damage at spent fuel pool are proposed for inclusion into Tier 1. These lists have been used as basis for detailed fragility evaluation for selected SSCs under METIS project, /METIS 2025/.

4.1.2. Probabilistic modelling

The discrete approach, see Section 3, has the main advantage: seismic sequences and/or MCS can be directly defined by the PSA model. It also allows the use of common existing PSA software, as well as the METIS tool, to implement seismic PSA and thus the implementation of seismic PSA as part of the integrated full-scope PSA model.

Example of discretization is presented in Figure 16.

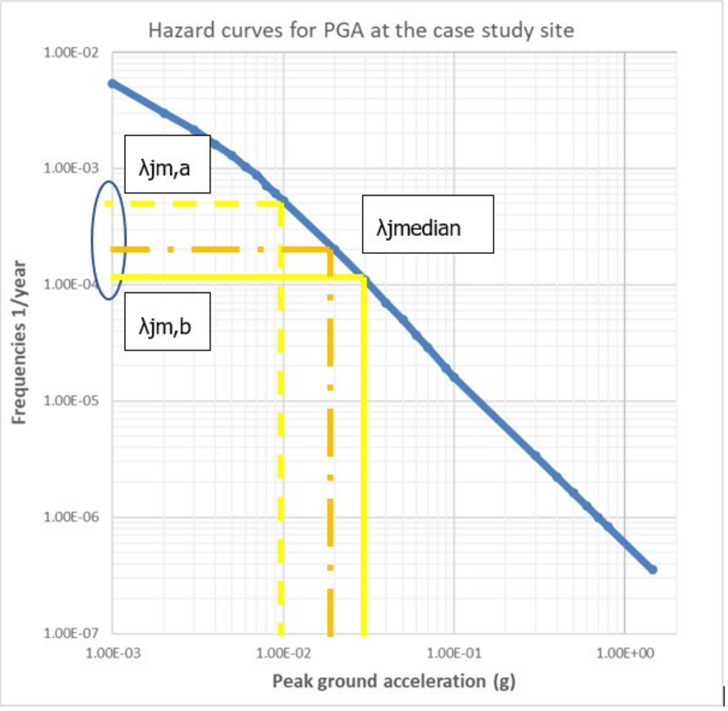

Figure 21 Example of hazard curve discretization

Several approaches can be used to implement the discretization process:

A. use upper bound of the interval. Seismic event frequency calculated for higher PGA (λjm,b in Figure 16) is combined with SSC failure probability (point value) for the same PGA. The approach was used in the METIS base case, /ZNPP 2019/;

B. use median value within the interval. Seismic event frequency calculated for the median PGA (λjmedian in Figure 16) is combined with SSC failure probability (point value) for the median PGA. Example is presented in /IAEA 2020/;

C. use average frequency for the seismic interval. Averaged frequencies are combined with averaged failure probabilities (the mean of the interval) from the SSC fragility curves;

D. use difference between the upper and lower bounds of the frequencies at the interval ends, (i.e., λjm,a - λjm,b). The approach is implemented in commercial seismic PSA software /RISK 2013/.

Figure 22 illustrates differences in results of CDF calculations due to different approaches for calculation of seismic frequencies.

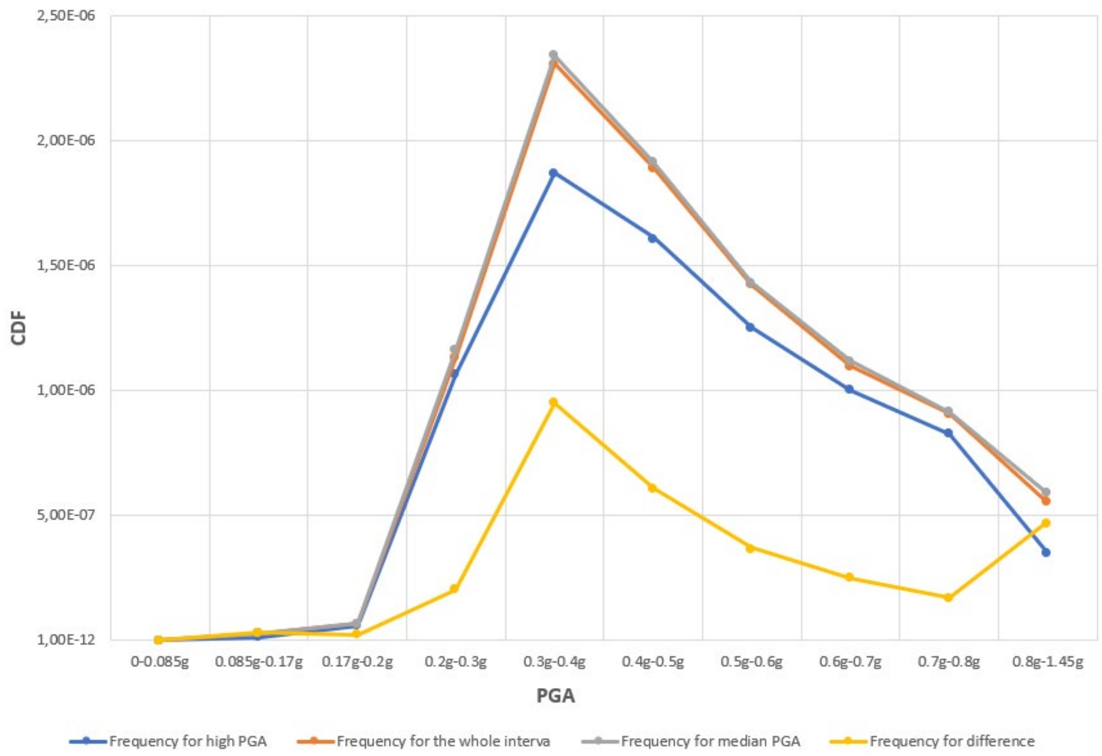

Figure 22: Sensitivity of CDF to seismic frequencies

Figure 23 illustrates sensitivity of CDF to failure probabilities of risk-important SSCs that are quantified by different discretization approaches.

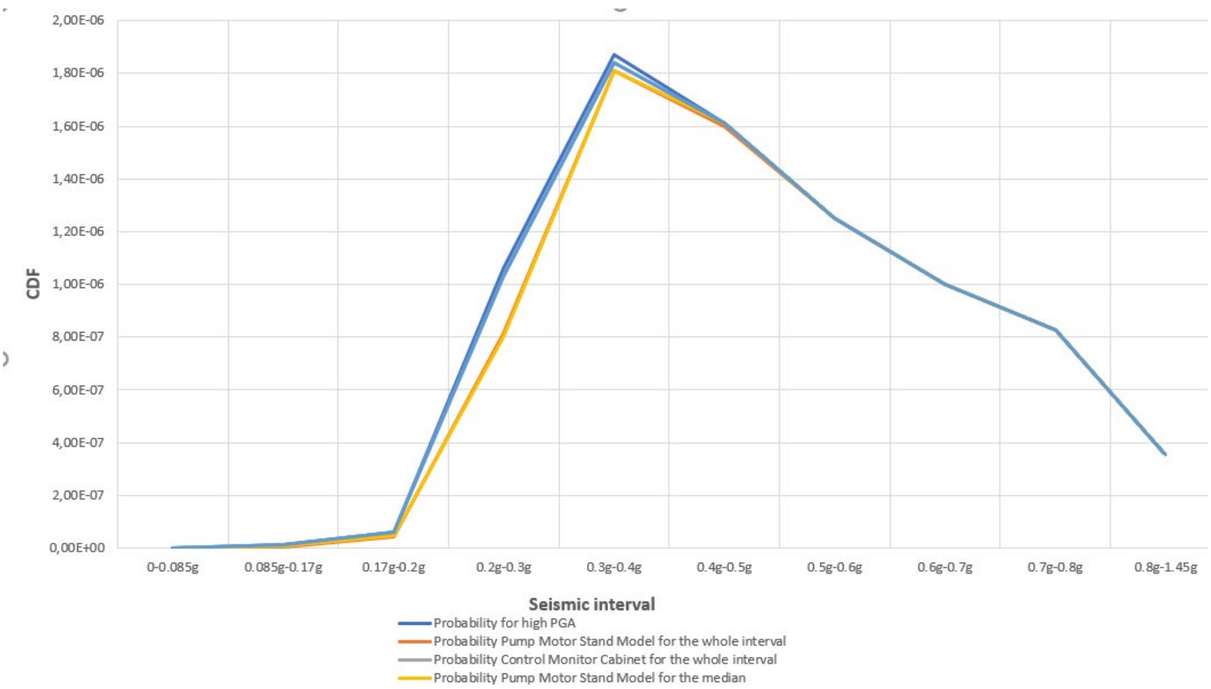

Figure 23 Sensitivity of CDF to SSC probabilities /METIS 2025b/

Sensitivity analysis to the seismic event frequencies has showed that the most conservative results were obtained using average frequencies for considered seismic interval. The least conservative results were obtained using frequencies defined by approach from /RISK 2013/. In addition, it looks that approach

D may produce incorrect results depending on selection of seismic intervals. It is recommended for real SPSA to use average frequencies for seismic interval, and quantify these frequencies using reasonable (10-100) number of bins within the seismic interval. Increasing number of bins gives more precise, more accurate calculation of the frequencies.

The same approach that is used for quantification of the seismic event frequencies should be used for calculation of failure probabilities from the SSC fragility curves.

Example of CDF sensitivity to the quantification approaches is shown on Figure 23.

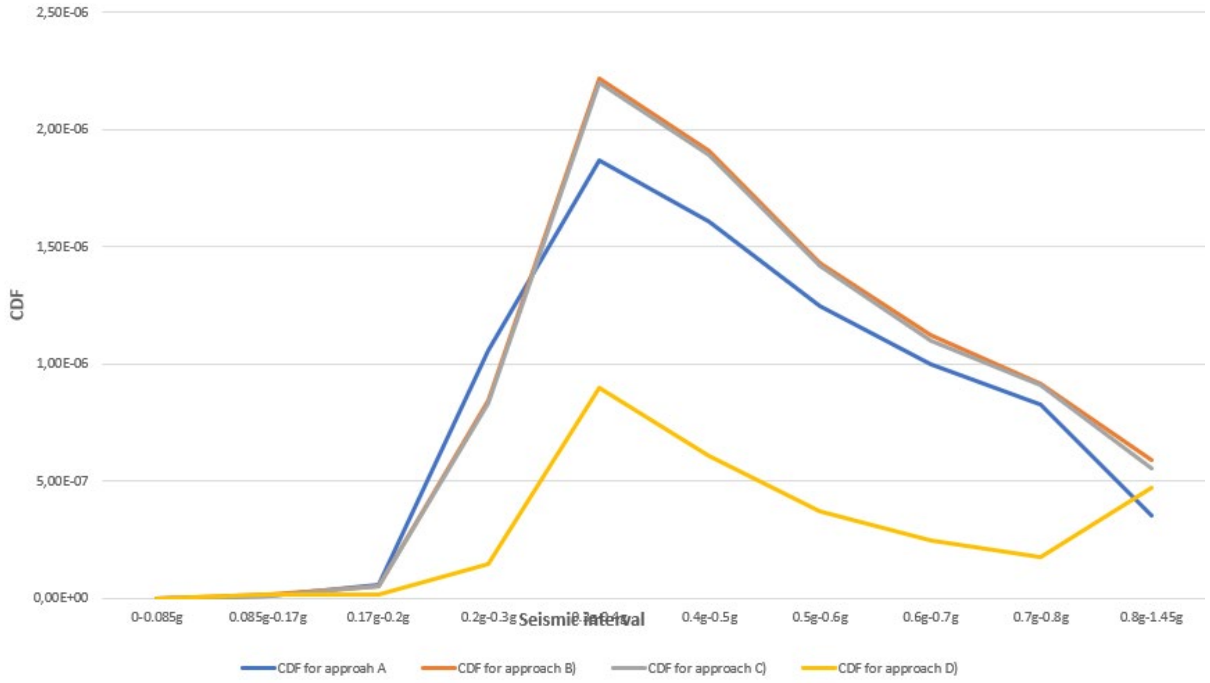

Figure 24: Sensitivity of CDF to discrete approaches

It can be concluded that approaches B or C could be recommended.

Regarding the seismic correlations, the approach from 2.2 was applied for the METIS study case. According to the calculations, CDF is not sensitive to variations on degree of partial correlations for non-dominant SSC. However, for dominant contributors the CDF can be treated as sensitive. As shown in Figure 20, for certain seismic intervals the CDF is changed due to variations of correlation coefficient for two dominant contributors from 0,75 to 0,8.

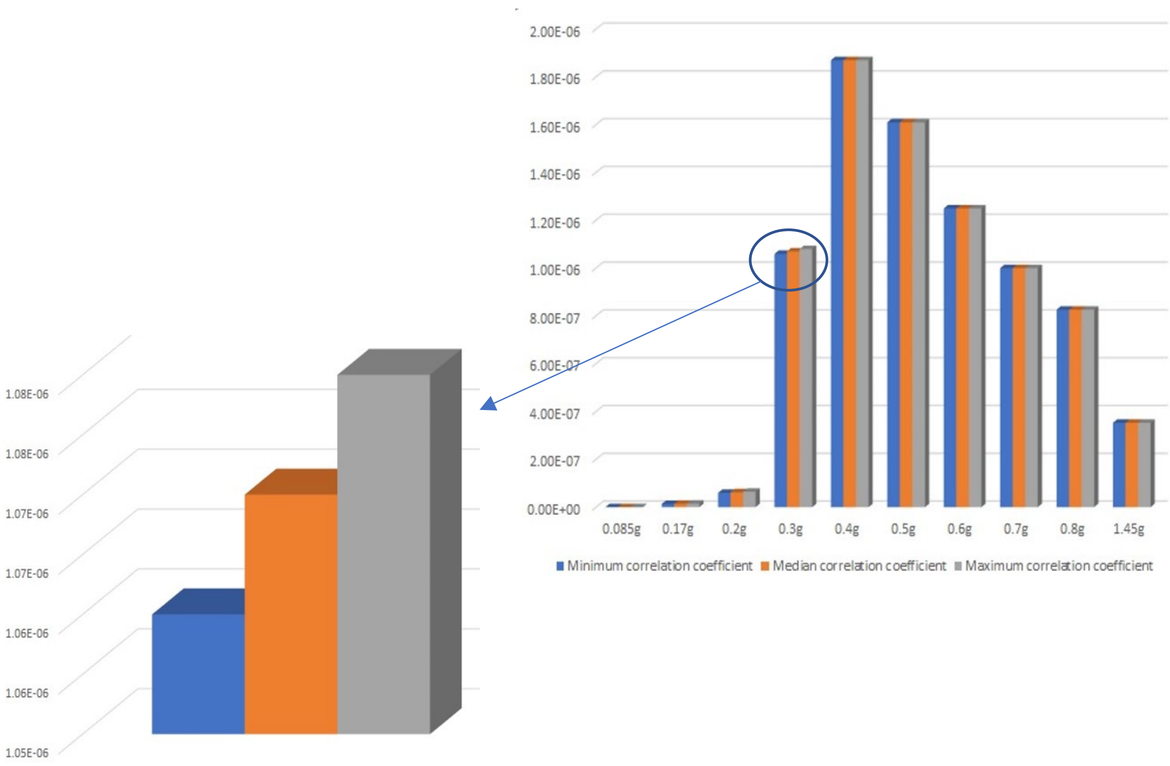

Figure 25: Sensitivity of CDF to degree of partial correlations for dominant SSC, /METIS 2025b/

It can be recommended to identify dominant contributors for each seismic interval, and to assign reasonable correlation coefficients for set of dominant contributors within separate seismic interval. Recommendations regarding the definition of correlation coefficients are presented in Section 2.1 of the METIS deliverable 7.7, /METIS 2024/.

The test modeling of aftershocks was performed as part of strategy for consideration of aftershocks in seismic PSA, taking into account the following input data and assumptions: POS "Operation at full power" during the mainshock; group of initiating events QS1 "Primary leaks in containment S1, S2, S3"; mainshock Q4 with PGA=0.3g and 2.00E-05 frequency; aftershock AS (A1) with PGA=0.17g and 5.00E-01 postulated probability after the mainshock; accident sequences that lead to damage of the reactor core resulting from the mainshock are not considered in the aftershock analysis. For the test modeling, the model and input data (including the SSC fragility curves) of the Zaporizhzhia NPP Unit 1 SPSA were used. The test calculation results showed that the aftershock made a small contribution to the CDF for the low intensity area of Zaporizhzhia NPP Unit 1 SPSA (test case performed to support the Strategy): lower than 1% in the SAPHIRE test model and about 2% in the RiskSpectrum PSA test model.

For test calculation to determine the influence of aftershock on CDF considering the "intermediate damage state" of the ZNPP Unit 1 reactor compartment building, combinations of seismic effects were addressed. The contribution to the core damage frequency was assessed for the following combination: mainshock with PGA=0.5g and 3.61E-06 frequency and subsequent aftershock with PGA=0.3g and 5.00E-01 postulated probability after the mainshock reached ~ 11%.

Before starting the SPSA analysis considering aftershocks, the following caveats are very recommended to be taken into account: the most likely risks arising from aftershock would occur when the NPP is subjected to a mainshock larger than the design basis, but smaller than would cause a core-damage accident; some SSCs might suffer some damage – not enough damage to cause them to fail to perform their safety function ("intermediate damage state"). Then the aftershock occurs later, and that SSC (now weaker than it should be) is more vulnerable, and the aftershock causes it to fail. For a "full scope aftershock SPSA" to provide the usual insights it is expected from a seismic PSA it would be required to analyze accident sequences in which one or more SSCs are in an intermediate damage state arising from the mainshock. The initial condition for the aftershock SPSA is that the SSC still performs its safety function, but is weakened. At the beginning of the analysis there is essentially zero information concerning how to characterize those intermediate damage state situations. Many issues would require shake-table testing: shake-table testing that causes some damage but at input levels lower than the "damage threshold" defined as "the SSC cannot perform the safety function" - That would be the intermediate state of the item, after the mainshock but before the intermediate damage state; shake-table testing with that equipment item, partially damaged by the simulated main earthquake, and shake it more (the aftershock simulation) until it truly cannot perform its safety function. Without that data, a realistic full intermediate damage state SPSA is not feasible.

The other way is to perform a "conservative" or "simplified" SPSA using demonstrably conservative PSA-type analyses or simplified PSA evaluations, but keeping a target objective of achieving realistic safety significance (or not) of aftershocks consistently with experience feedback and observations. For example, after analyzing the plant design, safe shutdown paths, etc., SSCs that can be potentially damaged in the event of a mainshock of specific level are selected (i.e., the corresponding damage is "assigned" to them). Further, failures in the event of an aftershock are "assigned" to the selected SSCs, which will accordingly influence the change in their fragility curves in relation to those used in the mainshock SPSA. Aftershock SPSA is then performed according to the procedure described in the Strategy. It should be taken into account that the assignment of damage/failure to SSCs strongly depends on the site seismic intensity level (levels of considered mainshocks and aftershocks).

There is one more very important type of information that can be obtained using SPSA tools: the safety concern is that a mainshock has not caused a core-damage accident, but an aftershock would do so, because some SSCs are weakened. The information that could be derived using SPSA tools, given the appropriate guidance, is identification of those SSCs that are both required in terms of their post-mainshock seismic safety function and also might find themselves in a seriously weakened "intermediate damage state." These would be the SSCs to worry about vis-a-vis aftershocks. Once those are identified, it should be feasible to direct the plant staff, in the immediate aftermath (first few hours) after the mainshock, to inspect each such SSC and determine whether (or not) it has been seriously damaged (even though it still performs its safety function) and, if so, whether anything can and should be done for that SSC to help keep the plant safe if an aftershock were to occur. The list of SSCs to inspect urgently should be short, and very high priority could be assigned to examining them.

The extensive analysis of experience feedback, including recent experiences in Japan, as well as experimental test setups with earthquake sequences showed that today there is no evidence for specific sensitivity of NPP to aftershocks (see D7.4).

Based on the analyses performed during the development of this Strategy, the following key notes could be recommended for future studies of considering aftershocks in SPSA:

- The goal of an aftershock evaluation would be to identify SSCs necessary to maintain the plant in a safe shutdown state and assess their potential vulnerability to aftershocks or perhaps to guide post-earthquake inspections.
- Significant challenges exist in developing fragilities for SSCs that consider the damage state due to the mainshock. For SSCs not damaged by the mainshock, the fragility should be the same as before the mainshock.
- The systems model should simulate the post-earthquake shutdown state of the plant.
- Future research into these areas would be necessary to optimize aftershock SPSA evaluations and determine the appropriate insights

This is a challenge for SPSA developers considering aftershocks to choose and substantiate such SSCs and their "intermediate damage state". Some items which are important for analysts are as follows:

- Selection of mainshock and aftershock characteristics for the sensitivity analysis (for example, from a de-aggregation of hazard, selection of a reference earthquake etc.);
- Selection of critical safety functions, in case that the plant has been successfully shutdown (for situations where no core damage has occurred) after an MS and continued cooldown;
- Selection of critical systems and subsystems to fulfill the required safety functions (for example, residual heat removal and supporting systems);
- Identification and evaluation of the post-mainshock status of SSCs associated with the systems that are vulnerable to damage;
- Estimate of the fragility shift (where applicable).

Application of PSHA vector-valued analyses and vector-valued fragility analyses for METIS study case has been discussed in the project. Although vector-valued analyses can provide a higher level of accuracy than scalar analysis, the use of vector intensity measures often entails a cost that, in many cases, may outweigh the benefits of achieving a more precise prediction of engineering demand parameters. For this reason, the scalar analysis was selected to be applied for the case study.

4.2. Seismic PSA software aspects

The following technical requirements to seismic PSA software are outlined in /METIS 2022/:

- The discretisation process should allow to consider the different fragility levels, and provide practical means to help analysis apply the discretisation given external data.
- In seismic PSA, for a given seismic intensity level, both the uncertainty related to the SSCs failure probability (obtained from the fragility curve) and the probability or frequency of the considered seismic intensity (obtained from the hazard curve) need to be considered in a comprehensive framework. For considering uncertainties the seismic PSA tool has to ensure the following specifications: Data uncertainties have to be included by assigning probability density functions to basic events. This has to consider all the different shapes or expressions these functions may be. Introduce a way to consider fragility curves that model the conditional probability of failure of a SSC in a seismic event which are expressed as functions of the seismic load intensity. The seismic hazard curve is also subject to uncertainty and therefore it should be expressed depending on the return frequency.
- The computation of Seismic PSA models is not straightforward and should consider an accurate treatment of negations: The negation are fully implied since we deal with success paths (in the event tree approach). The existence of non rare events because of the seismic events, may introduce some bias in the quantification process if we apply some well known approximations whenever success branches are involved (they turn to negated gates). Therefore, the quantification may be too optimistic.
- The computation of Seismic PSA models should consider an accurate treatment of approximations. In the quantification process, there are some shortcuts to accelerate the computation but which are conditional upon some assumptions that may not hold in the case of seismic events (independence and non existence of high probabilities). On has to consider adopting more exact calculations which have some consequences on the computational time.

- The solver engine has to consider the possibility of dependence of events which is one of the main PSA assumptions. Therefore, it could be necessary to get out of the traditional PSA solving algorithms to deal with such context. May be new developments are needed or at least a very careful analysis have to be done whenever dependence can be found.
- CCF for large groups. Standard CCF approaches deals with limited number of SSCs within CCF group (2,3,4-8). The question of dealing with large CCFs is not straightforward and need a development of sound methodologies. By experience, the solvers have their own way of computing and encoding CCFs. There are some limitations by the solvers in the expression of the number of components under CCFs when they are too many. But there may be conservative simplifications. The other limitations are related to the availability of experience data. Lump sum values or mapping up methods can be used.
- Considering non rare events is not in the scope of the OPSAMEF extension. There may be additional attributes that can be added in the implementation of the formalism in PSA tools, to allow considering impact of the non rare event on the function events where algorithmic specifications (ignore success branches, delete term) can apply. This may be helpful for considering the appropriate algorithms in such situations and prevent the user from using weak approximations.

Further improvements may be considered regarding the METIS tool:

- Code debugging to ensure more stable operation of the solver at different platforms;
- Further integration and debugging of software within the METIS tool package;
- Improvement of the solver to correctly treat initiating event frequencies.

5. Conclusions

Overview of WP7 activities is presented. It includes summarization of works done to develop the METIS tool, to test and benchmark this tool. Modelling approaches related to selected aspects of seismic PSA have been assessed and modified. Such important topics like: preparation of seismic equipment list, modelling of impact both mainshocks and aftershocks, consideration of seismic correlations between SSC, accounting impact of seismic events on human reliability analysis; are presented.

Based on the results of developments and probabilistic calculations several insights have been defined and discussed. Associated proposals regarding performing seismic PSA are prepared.

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