Horizon 2020
Programme

METIS

Research and Innovation Action (RIA)

This project has received funding from the European
Union's Horizon 2020 research and innovation programme
under grant agreement No 945121

Start date : 2020-09-01 Duration : 48 Months

Specification of the PSA format

Authors : Dr. Mohamed HIBTI (EDF)

METIS - Contract Number: 945121

Project officer: Katerina PTACKOVA

Document title	Specification of the PSA format
Author(s)	Dr. Mohamed HIBTI
Number of pages	0
Document type	Deliverable
Work Package	WP7
Document number	D7.1
Issued by	EDF
Date of completion	2022-04-29 11:02:09
Dissemination level	Public

Summary

For the task 7. 1 a state of the art study is ongoing with an update with the recent methodologies and tools that were used in the Industry. Many issues were identified about the discretisation process, sampling, uncertainties, model dependencies , impact of considered the modeling approaches, non rare event consideration and on the algorithms that were/are used to compute relevant PSA metrics. An important effort were made to avoid overestimation of frequencies, wthus an attention was made to the way negation and dependencies are considered. Many tools started implementing BDD or BDD driven algorithms. As expected many of these implementations suffer from computation complexity in time and space and a trad-off should be found between the need of a systematic use of such algorithms and their introduction only when it is needed. Other approaches use Simulation (e.g. Monte Carlo Simulation) to consider the shape of the fragility curves and are sometimes combined with onventional approaches (rare event approximation or Min cut upper bound approximation for instance) but still need more refinement for industrial use. The aim of this sub task of the METIS project is to develop new representation format for probabilistic safety assessments models. Regarding more specifically seismic PSA, it will be an essential tool to exchange models, to incorporate fragility curves and to implement model rewriting techniques. The Open PSA format is adopted for this task as a universal format that may be shared by different actors with the following objectives: - Identify and detail modelling issues, gaps and shortcomings to be resolved in new seismic PSA tool; - Develop technical requirements (specification) to new seismic PSA tool; - Incorporate in the format all what is needed to perform seismic PSA, including hazard curve, seismic fragilities, seismic correlations and their variability parameters; - Revisit the format to incorporate recent results of model-based systems engineering - Update modelling environments and calculation engines to take into account the new version of the format.

Approval

Date	By
2022-04-29 12:20:54	Mr. Oleksandr SEVBO (Energorisk)
2022-05-02 15:56:44	Dr. Irmela ZENTNER (EDF)

Research and Innovation Action

NFRP-2019-2020

TASK 7.1 Development of an open-source representation format for PSA models

Deliverable D7.1

Version N°1

Authors: HIBTI Mohamed (EDF)

This project has received funding from the Horizon 2020 programme under grant agreement n°945121. The content of this presentation reflects only the author's view. The European Commission is not responsible for any use that may be made of the information it contains.

Disclaimer

Document Information

Grant agreement	945121
Project title	Methods And Tools Innovations For Seismic Risk Assessment
Project acronym	METIS
Project coordinator	Dr. Irmela Zentner, EDF
Project duration	1st September 2020 – 31st August 2024 (48 months)
Related work package	WP 7
Related task(s)	Task 7.2 - Development of a dedicated seismic database management tool
Lead organisation	EDF
Contributing partner(s)	
Due date	31st March, 2022
Submission date	25/02/2022
Dissemination level	X

History

Version	Submitted by	Reviewed by	Date	Comments
N°1	Mohamed Hibti	Tu-Duong	25/02/2022	
		Oleksandr Sevbo	17/03/2022	
		Irmela Zentner	25/03/2022	
		Nicolas Duflot	11/04/2022	
		Hugo Jadot	12/04/2022	

Contents

1 Introduction **6**

2 Open PSA exchange format **7**

3 PSA general issues regarding modeling and quantification **7**

3.1 Main uncertainties in SPSA models 8
  3.1.1 Reliance on hazard curve 9
  3.1.2 Uncertainty related to the identification of the SEL 9
  3.1.3 Uncertainty related to the establishment of fragility curves of SSC 9
3.2 Discretisation process 9
3.3 Computation 10
3.4 Model dependencies 10
3.5 Implicit dependencies 10
3.6 Non Rare events consideration 11
3.7 Lack of publicly available studies 12

4 Existing Software **12**

4.1 Riskspectrum 12
  4.1.1 RiskSpectrum®HazardLite for hazard preparation 12
  4.1.2 C-BDD (RiskSpectrum®) 12
4.2 ACUBE (EPRI) 13
4.3 Uncert 13
4.4 PRASSE 14
4.5 EQESRA 14
4.6 MASTODON 14
4.7 SECOM2-Boolean 14
4.8 AIMS-PSA 15
4.9 SAPHIRE 15

5 Technical requirements and specifications to new seismic PSA tool **15**

5.1 Discretisation process 15
5.2 Uncertainties 16
5.3 Computation 16
5.4 Dependencies 16
5.5 CCF beyond 4 and 8 16
5.6 Non Rare events considerations 17

6 Extension and implementation in OPSAMEF **17**

7 Implementation in Andromeda **17**

7.1 Specific approach 17
7.2 Generic approach 18
7.3 UI extensions 18
7.4 Additional scripts for data preparation 18
7.5 Interaction between Andromeda SCRAM and the seismic database developed in the WP7.2 19

8 Conclusion **19**

References **20**

A Seismic Calculations **23**
A.1 Quantification of the hazard frequency 23
A.2 Fragility computation 23
A.3 Uncertainty calculation 24

Abbreviations and Acronyms

Acronym	Description
ACUBE	Advanced Min Cut Upper Bound Estimator
BDD	Binary decision diagram
CCF	Common Cause Failures
CDF	Core Damage Frequency
MCSs	Minimal Cut Sets
MCUB	Min Cut Upper Bound
MFT	Master Fault Tree
NP	Non deterministic polynmial
NRC	Nuclear Regulatory Commission (NRC)
OPSAMEF	Open PSA Exchange Format
PDF	Probability density function
PGA	Peak Ground Acceleration
RAE	Rare Event Approximation
SDB	Seismic Data Base
SIET	Seismic Initiating Event Tree
SSC	Structures, Systems and Components
SSCs	Structures, Systems and Components
WP	Work Package

1 Introduction

Seismic probabilistic risk assessment (SPRA) deals with the quantification of seismic risk as a probability/frequency of an earthquake leading to the occurrence of an undesirable event (e.g., core melt or release of radioactive material outside a nuclear power plant). It involves performing probabilistic seismic hazard analysis, calculating the probabilistic seismic demands on *Structures, Systems and Components* (SSCs). For a given seismic hazard, estimating the vulnerability of the SSCs in terms of seismic fragilities (probability of failure for a given seismic shaking intensity or an engineering demand parameter), and convolving the seismic hazard and the vulnerability to calculate the risk of the undesired outcome (cf. [36]).

Almost all the methods and software used in the SPRA for nuclear facilities are based on the generation of cutsets or prime implicants[1] that are summed up to get the probability or the frequency of the undesired outcomes. The generation of cutsets is done via Boolean reduction or the construction of a *Binary decision diagram* BDD of the *Master Fault Tree* (MFT) representing the analysis case that is calculated. The problem of generating cutsets is known to be NP-complete (cf. [27]) as well as the construction of optimal BDDs (cf. [18]). Therefore, there are important computational issues regarding the computation with great accuracy of the main PSA metrics. Up to know, for PSA models for nuclear power plants, the approximation based approaches are mainly used for generating cutsets assuming independence between basic events, which implies a number of issues when dealing with non rare events and correlation, which is mainly the case for the SPSA.

Dependencies introduced by the seismic events may be explicit (e.g. sharing the same support system) or implicit (e.g. *Common Cause Failures* CCFs, or seismic induced dependencies such as same location, same altitude . . .). In the last case, there are two main concerns, the soundness of the assumptions upon which the mathematical foundations of the fault tree analysis are based. The second is the expression of theses dependencies in such a way to reduce the impact of the dependencies on the assumptions in question.

The aim of this sub task of the METIS project is to develop new representation format for probabilistic safety assessments models. Regarding more specifically seismic PSA, it will be an essential tool to exchange models, to incorporate fragility curves and to implement model rewriting techniques. The Open PSA format is adopted for this task as a universal format that may be shared by different actors:

- Identify and detail modelling issues, gaps and shortcomings to be resolved in new seismic PSA tool;
- Develop technical requirements (specification) to new seismic PSA tool;
- Incorporate in the format all what is needed to perform seismic PSA, including hazard curve, seismic fragilities, seismic correlations and their variability parameters;
- Revisit the format to incorporate recent results of model-based systems engineering
- Update modelling environments and calculation engines to take into account the new version of the format.

The SPSA model process can use a seismic pre-tree, i.e., the *Seismic Initiating Event Tree* (SIET), to sort out the more pervasive effects of a seismic event that can lead directly to core damage or to a degraded plant condition[2].

---

[1] We speak about prime implicants which are cuts involving negated events. But for the sake of simplicity of will use the term cutsets for the prime implicants too.

[2] Peach Bottom Atomic Power Station (PBAPS), Units 2 and 3 Seismic Probabilistic Risk Assessment in Response to 50.54(f) Letter with Regard to NTTF 2.1 Seismic Revision O August 28, 2018.

The evaluation is then continued in other systemic event trees that evaluate the plant response (component, systems and structure in addition to human actions) and mitigation capability given the preconditions established in the SIET.

Different algorithms are used to calculate the frequency of the relevant/undesired end-states.

In this paper, we identify some of the common issues that have been proved to have an impact when dealing with the evaluation of seismic PSA as a first step before specifying the requirements for a modern, open and more accurate SPSA solver.

2 Open PSA exchange format

The *Open PSA Exchange Format* (OPSAMEF) is a result of the *Open Initiative for Next Generation PSA* (cf. [14]) whose aim was to provide an open and transparent public forum to disseminate information, independently review new ideas, and spread the word with emphasize on openness. It is a structured `XML` format intended to express the main requirement for the representation of a PSA model.

This initiative followed a series of debates raised following a number of issues regarding large, safety critical PSA models (cf. [13]) and many questions that have followed:

- Quality assurance;
- Un-founded 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.

OPSAMEF is now used in many PSA tools either as an internal format or an input/output format with import/export capabilities ([33], [16], [42], [7])[3] and has helped to develop many new functionalities, with the state of the art of modern software development practices, that helped PSA practitioners to develop, document and navigate their PSA models ([15]).

In this report, we review the main needs of the SPSA models to extend the format accordingly, and see what may be the impact of these new extensions on the way solver engines can handle the corresponding analysis cases.

3 PSA general issues regarding modeling and quantification

In this section, we present some of the main issues regarding seismic PSA modeling and evaluation.

PSA software allow data uncertainties to be included by assigning probability density functions (pdfs) to basic events[4].

---

[3] The main commercial tool may also have their opsamef import/export format.

[4] representing System Structure or Component (SSC) failures.

However, the fragility curves that model the **conditional probability** of failure of an SSC in a seismic event are expressed as **functions of the seismic load**. The conditional probabilities are themselves uncertain.

An approach for deriving the *Core Damage Frequency* (CDF) for core melt probability using probability distributions that accounts for both the SSC fragility curve and the uncertainty in the seismic initiating event is proposed in [32].

The method employs a single-step Monte Carlo method to derive the CDF of core melt frequency using a simplified seismic event tree for a PWR type reactor. The method is compared to results obtained using a nested Monte Carlo method. Another approach is adopted in [35] and is based on combination of Monte Carlo Simulation and the *Rare Event Approximation* (RAE) and *Min Cut Upper Bound* MCUB methods. After generating *Minimal Cut Sets* (MCS) using REA and MCUB, Monte Carlo Simulation method is used to compute the exact CDF and MCSs.

The importance of including data uncertainties in SPSA arises from the non-linearity of PSA models and the cliff-edge nature of seismic fragilities (sliding, buckling, contact), which can result in uncertainties impacting the calculation of the mean core melt frequency as well as its probability distribution. Therefore, the **separation-of-variables** method **assumes linearity** and the applicability of the **individual parameters** provided in the EPRI guidance (e.g. beta for random phasing) is questionable whenever we deal with strong non linearity (cf. [38]).

The PSA methods found in literature include in their analysis the uncertainty of the seismic frequency for an event of a known acceleration, and only make use of this uncertainty in the last step when estimating the cumulative frequency of core damage.

The uncertainty in the hazard evaluation is only considered by uncertainty in the hazard frequency, but the acceleration associated to each frequency is fixed (cf. [34, 23] cited by [31]). One should consider the uncertainty on the acceleration for a fixed seismic exceedance frequency. The uncertainty on the acceleration is then considered when estimating the failure probabilities of components for events at a given exceedance frequency, and then the core melt frequency for the entire frequency range of seismic events is estimated, having included the uncertainty over the acceleration for all seismic events ([31]).

3.1 Main uncertainties in SPSA models

Uncertainties in SPSA are of many types. In addition to internal event uncertainties, there are other seismic specific uncertainties. In [9] and [39], three main types of uncertainties are considered; parametric, completeness and model uncertainties.

The parametric uncertainties are related to the reliability data of the PSA model and may result of different sources (observed data in the experience feedback, expert judgement, Bayesian based estimations, . . . etc). The parametric uncertainties should however be considered in SPSA and a special attention should be made to the way they are propagated through the model. Recall that there are some dependencies that may hold between some parameters (cf. sections 3.4 and 3.5).

Model uncertainties are related to the simplifications made in the model, to the different assumptions underlying it and the lack of a deep knowledge of the systems, components and structures in various conditions during accident situations. Considering such uncertainties is done through the modification of some assumptions that may imply model structure modifications, or the introduction of new elements (basic events, initiators, . . . etc). Some of these uncertainties are covered by doing sensitivity analysis.

While completeness uncertainty can involve either scope limitations or unknown issues (cf [40].), safety margins and conservatism in the success criteria definition and support studies provide protection against some of these issues.

Other symbolic uncertainties are due to the process of obtaining prime implicants or numeric due to the approximations while summing up cutsets probabilities (cf. [19]). These uncertainties tend to increase in the SPSA because of the existence of many non rare events in the model. These events are implied by the seismic events and other parametric uncertainties.

In [2] (appendix C), a non exhaustive list of uncertainty sources were identified and discussed. We present some of these sources (reliance on hazard curve, uncertainty related to the identification of the SEL and uncertainty related to the establishment of fragility curves of SSC) and discuss if there is a specific need that has to be considered in the Open PSA extension to allow its representation in the SPSA model.

3.1.1 Reliance on hazard curve

The hazard curve used to evaluate the occurrence frequency of seismic events is is based on historical seismic events, tectonic and geology of the region. In addition to the intrinsic aleatory aspect of seismic movements, the curve integrates the epistemic uncertainty related to the knowledge of the physical phenomena. Therefore, instead of a one curve, a family of curves is established each one is related to a given confidence level.

3.1.2 Uncertainty related to the identification of the SEL

The seismic equipment list may not be that complete or exhaustive and some components, systems and structures can be missing for different reasons[5]. However, as said before (cf. § 3.1), safety margins and conservatism in the success criteria definition and support studies provide protection against some of these issues (cf. [40]).

3.1.3 Uncertainty related to the establishment of fragility curves of SSC

For a given failure mode of a SSC, the fragility curve is defined as the best estimate of the median capacity (A_m) and the dispersion parameters[6]. In addition to the aleatory uncertainty (β_R) related to the variability of the component characteristic and the estimation of the seismic load, the curve incorporates the epistemic uncertainty (β_U) related to the modeling relevance regarding the material characterisation and their failure criteria, the expert judgement ... etc.

3.2 Discretisation process

In conventional PSA models such as RiskSpectrum or CAFTA basic event data cannot adjusted automatically to take into **account of changes in earthquake intensity**. Thus, analysts must discretise the hazard curve into discrete events of different frequencies of which is of an **assumed fixed acceleration**: this leads to the creation of multiple event trees each containing different basic event data for the seismically induced failures.

The process of discretising the hazard curve and **including uncertainties** in component failure probabilities as well as the hazard curve itself increases the complexity of the model and the effort needed to develop it.

In [31], Recommendations issued by the US Nuclear Regulatory Commission (NRC) in ref [1] state that Seismic hazards are to be classified as external hazards which should be incorporated into PSA models by including new initiating event frequencies and developing the appropriate system models.

The report recommends selecting appropriate failure events that will have a significant influence on the PSA outcome. NRC guidance document [21] emphasises the importance of allowing for uncertainties in equipment failure probabilities and in the ground motion associated with an earthquake, when performing a seismic PSA (cf. [31]).

In particular it states that an essential part of the SPSA methodology should be to consider both random and systematic uncertainties in the earthquake motion.

---

[5] Limitation of the scope, access difficulty or missing during walkdown activities. wrong application or interpretation of the seismic robustness criteria of the equipment.

[6] Dispersion parameters are a measure of how much a sample fluctuates around a mean value. Measurements of Central Tendency give the information about the centre of the data, dispersion measures give information how much the data is spread around this centre.

3.3 Computation

As a further problem with seismic models, because the conditional probabilities are large the models need to account for negated events [6]. This causes a large number of cutsets to be generated that are very similar to each other. For example, using the cutsets from above, the cutsets may include the negation of other seismically induced terms. For example, if the above combinations of events did not apply when the failure of event “D” or “E” did not occur, then the cutsets may look like the following:

```
SEIS_G8  A_G8  B_G8  -D_G8
SEIS_G8  A_G8  C_G8  -D_G8
SEIS_G8  A_G8  B_G8  -E_G8
SEIS_G8  A_G8  C_G8  -E_G8
```

In a typical Level-1 PSA, the negated D and E terms are often ignored, as the probability of the success is near 1.0. However, in the seismic case, the probability of success might be only .5. This leads to more cutsets, additional dependence between the cutsets, and high probability events, all of which makes the approximation less accurate. A key question is how much less accurate does this make the seismic application of the MCUB approximation.

3.4 Model dependencies

When dealing with PSA models there are different forms of dependencies. Some are explicit that can be modeled in an explicit manner such as support systems, electrical supply or cooling, but also common cause failures. Aside from CCFs all the structural dependencies are usually handled and do not require any additional treatment. The other forms of dependencies require more discussions. Indeed, one of the main assumptions of PSA is the independence of elementary failures. The seismic events can challenge this assumption and require a special methodologies, since they may be under **implicit dependencies**. If two or more components simultaneously fail by a single earthquake ground motion input, failures of these components are considered to be seismically dependent or seismically correlated (cf. [20]). Moreover, when components are on parallel trains to ensure redundancy, it seems (cf. [8]) that they may fall under dependency even if we do not consider components of the same type or the same technology[7].

CCF dependencies under seismic events may be extended to much more components than we are used to consider. Sometimes we may consider intra-system CCFs and event multi-site CCFs. This extension require adequate methodological treatment beyond standard models (more than 4 elements).

3.5 Implicit dependencies

In seismic PSA, some the elementary failures are related to each other due to the similarity of input earthquake ground motion and to CCF that may hold for different reasons.

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 ([30]).

Extraction from [30].

- *Seismic dependency is a function of two primary attributes, **similarity in seismic capacity** and **similarity in seismic demand**. Similarity in seismic capacity is a **function of the dynamic characteristics** (frequencies and mode shapes) of the component as well as the governing seismic failure modes. Similarity in the seismic demand is a function of the **dynamic response** (acceleration, velocity or displacement depending on the governing failure mode) at the anchor points of the components. With these basic tenets in mind, there are four types of situations*

---

[7] Indeed, the redundant components even diversified (different types or different technologies) located in the same building or in adjacent buildings can fail for a common cause related to the structure failure (Fall of wall , tank failure, etc).

requiring the PRA analyst to ponder over the potential seismic dependencies between component failures:

- ***Dissimilar Components at Different Locations****: Independence is judged appropriate*
- ***Dissimilar Components in Close Proximity****: Quantification methods treating these components as fully independent are thereby judged to be generally appropriate. However, if the components have approximately the* ***same fundamental frequencies*** *and* ***similar types of failure modes*** *then a case might be made that partial dependency exists.*
- ***Identical Components at Different Locations****: The variation in responses can be large enough to minimize the impact of dependencies, but this will vary considerably from case to case. Current quantification methods treating these components as fully independent may or may not be appropriate.*
- ***Identical (Redundant) Components in Close Proximity****: The standard SPRA practice of treating these components as fully dependent (i.e., "one fails, all fail") appears to be reasonable (and generally conservative) but may have a large impact on the accident sequence frequencies and on the insights of a seismic PRA. Needs more analysis.*

The main issue of representing and dealing with such dependencies is to consider including some seismic related attributes in the modeling of SPSA elements to express the considered dependencies in the model.

There are two main aspects:

1. Express this dependency on the SSC level and use an inheritance process or any other protocol to credit these dependencies.
2. Consider built-in parameters functions to express dependencies on the parameter level. This implies a treatment of the main PSA assumptions regarding the events independence.

3.6 Non Rare events consideration

EPRI [6] developed an advanced quantification (*Advanced Min Cut Upper Bound Estimator* (ACUBE)). Previous to the development of this method, the calculation of the plant risk was subject to conservatisms that could lead a plant to over-state the risk and thus inappropriately determining the significance of various plant systems, structures and components as well as plant configurations and operations.

The advancement in the quantification methods allows for the effective removal of overapproximation for the dominant cutsets. The dominant cutsets typically contain the largest magnitude overstatement in the results. In addition, successive model runs can also establish event importance for the seismic model.

Standard computational methods for seismic PSA use multiple Monte Carlo methods, making the calculations of the conditional core damage probability very computationally expensive [28, 3] (cited in [31]).

Example from [6]

```
SEIS_G8  A_G8  B_G8
SEIS_G8  A_G8  C_G8
```

If we suppose that $f(SEIS\_G8) = 1e^{-5}$, $p(A\_G8) = .4$, $p(B\_G8) = .5$, and $p(C\_G8) = .6$, we can estimate the frequency as (factoring the initiator out):

$$1E^{-5} \times ((.4 \times .5) + (.4 \times .6) - ((.4 \times .5).(.4 \times .6))) = 3.9E^{-6}.$$

The true value can be calculated for such as simple case as:

$$1E^{-5} \times ((.4 \times .5) + (.4 \times .6) - ((.4 \times .5 \times .6))) = 3.2E^{-6}$$

a result that is 22% lower than our estimated value. The difference of is related to the fact that these cutsets are not independent, but correlated with the presence of a common basic event (A_G8). This lack of accuracy is cumulative, and it increases as the model gets more complex.

3.7 Lack of publicly available studies

There is a lack of credible and reproducible publicly available studies in the seismic PSA literature. One of the objectives of the METIS project is to make possible the use of open tools to share insights on the topic and hopefully develop benchmarks that can be used publicly and help enhancing methodologies and practice.

4 Existing Software

In this section we present a non exhaustive list if software that deal with these seismic issues.

4.1 Riskspectrum

RiskSpectrum®is the well known PSA Software by LLoyds Register. In this section, we will focus on the main aspects regarding hazards and the way the tool solves some of the difficulties identified in this document (cf. sections 3.1, 3.2, 3.1.1 and 3.6).

4.1.1 RiskSpectrum®HazardLite for hazard preparation

RiskSpectrum®HazardLite (cf. [3], we will refer to it later on as HazardLite) is a tool for simplifying modelling of hazards in general, and particularly seismic hazards in RiskSpectrum PSA.

HazardLite allows to prepare the necessary data for fragility calculations of components over discrete ranges of peak ground accelerations to be used for the computation of initiators and other basic event frequencies/probabilities. The tool can help considering uncertainty of fragility and hazard curves[8].

HazardLite produces, for each interval, the hazard frequencies and the fragility[9] to be used in the PSA model. The obtained basic events (initiators or standard basic events) are then produced and can be imported in the PSA model.

4.1.2 C-BDD (RiskSpectrum®)

Like in ACUBE, the MCS BDD algorithm [5] partitions the MCS list into one part which is converted to a BDD and quantified and another part which is quantified using MCUB. Moreover a number of options can be used by the user to decide a number of treatment by the quantification tools:

MCS Limit which part of the MCS list can be calculated using BDD algorithm/Shannon decomposition

Pivot Q and FV Limits within the BDD part of the MCS Q limit and FV limit parameters are used to decide which events should be treated exactly and which should be treated approximately.

---

[8] The user must enter the median acceleration A_m, the logarithmic standard deviation β_R, and the logarithmic standard deviation β_U.

[9] To reduce the amount of necessary seismic fragility events, fragilities may be grouped (using `OR`-structures) and combined when several fragility events are found in the same MCS (cf. [3]).

Maximal number of nodes Is the maximal number of nodes allowed in the BDD. This is used to limit the scope of the BDD usage and limits the size of the BDD to a reasonable tractable instance.

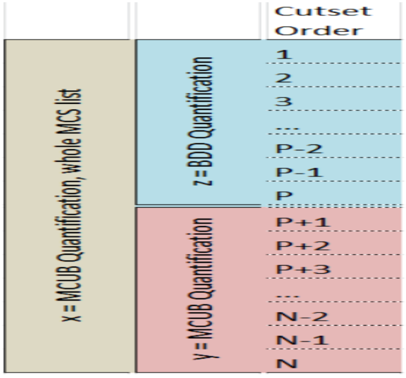

Figure 1: MCS BDD quantification based on MCS Limit

4.2 ACUBE (EPRI)

ACUBE [19, 12] apply on cutsets, and assume fault tree linking.

- Based on the example below there is an indication on the presence of negated events.
- How they deal with success branches if any? The negated events seems to be either introduced by the user or introduced using event tree structure.

Based on a user input threshold, it divides the cutsets into two groups

- a “major” group that contains the most contributing cutsets,
- and a “minor” group containing the remaining cutsets.

For the “major” group, the total of the cutsets is calculated exactly (in the case of ACUBE, this is done using a **BDD approach**), and for the minor group, the cutsets are calculated using a traditional **MCUB approach**.

The overall estimated result is then calculated as the combination of the major and minor group.

When performed correctly, this leads to a better estimate of the target model than provided by traditional MCUB calculations. It also provides a means by which the user can control the tradeoff between computational time and precision of the result, and even provide an estimate of the precision level of the result.

4.3 Uncert

UNCERT is a software that uses CAFTA generated cutsets and PRA databases as inputs to quantify the parametric uncertainty distribution of a group of cutsets.

The algorithm processes the trial results to form a probability distribution of the sampled SCDF and SLERF result. Indeed, it randomly samples from each of the input distributions, in conjunction with the **Type Code database**, and interfaces with the ACUBE algorithm **at each sample** to compute the **best estimate** result of the CAFTA cutset file (cf. a detailed description can be found in [4]).

4.4 PRASSE

PRASSE (Probabilistic Risk Assessment of Systems for Seismic Events) [24] is a solver of Boolean expressions using BDD algorithms method to represent the exact results of prime implicants. It includes a sampling based uncertainty analysis engine for estimating the plant level fragility (either the Monte Carlo Simulation or Latin Hypercube Sampling method). It also includes a seismic correlation module to consider failure probabilities induced by a correlation of response and capacity under an earthquake vibration.

4.5 EQESRA

The EQESRA software developed by EQE International INC [25] to evaluate the probability distribution of system failure frequency from information about component fragilities (seismic or non-seismic failures), Boolean expressions for accident or event sequences, and seismic hazard. The program performs component combinations in accordance with the Boolean expression to yield an overall system or plant level fragility (cf. [8]).

In [8], EQESRA convolves the system fragility with the seismic hazard to yield a probability distribution on failure frequency, which was translated into basic scores for comparison to results from the simplified methods. The EQESRA™ program uses the methodology described in [23] [22]. Based on these analyses, the following simple rules were developed for scoring:

1. When a group of components is linked by an "and" gate (indicating dependency), the overall score for that group is the lowest of the component scores, S min .
2. When a group of components is linked by an "or" gate (indicating redundancy), the overall score for that group is the highest of the component scores (S_{max}) plus a factor (f). This factor depends on the number of components (N) linked in parallel and takes the form: $f = 0.5(N-1)$. So the score for a redundant group of components is:

$$S_max + 0.5(N-1)$$

.

4.6 MASTODON

Multi-hazard Analysis of Stochastic Time-Domain Phenomena MASTODON (cf. [41]), implements seismic analysis and risk assessment tools in a quality-controlled environment. MASTODON is built on MOOSE (Multi-physics Object-Oriented Simulation Environment), which is a highly parallelizable, NQA-1 conforming, coupled multiphysics, finite-element framework developed at Idaho National Laboratory. MASTODON is capable of fault rupture and source-to-site wave propagation using the domain reduction method, nonlinear site response, and soil-structure interaction analysis, implicit and explicit time integration, automated stochastic simulations, and seismic probabilistic risk assessment. When coupled with other MOOSE applications, MASTODON can also solve strongly and weakly coupled multiphysics problems.

4.7 SECOM2-Boolean

SECOM-2 was developed at the Japan Atomic Energy Research Institute (JAERI) [29] and allows the main necessary[10] computation for seismic PSA analysis with limitations that are inherent to the solver that is used for the quantification, namely Wam-Bam computer code developed by EPRI in the early 70's ([26]).

---

[10] Calculation of component failure probability, extraction of minimal cut sets (MCSs) from a given fault tree (FT), calculation of frequencies of accident sequences and core damage, importance analysis with several measures with consideration of unique parameters of seismic PSAs, sensitivity analysis, and uncertainty analysis [29].

4.8 AIMS-PSA

AIMS-PSA is a PSA manager software developed by KAERI (Korea Atomic Energy Research Institute) with fault tree, event tree and cut set browser modules ([17]). The quantification is provided by FTREX (cf. [11]).

4.9 SAPHIRE

SAPHIRE was developed for the Office of Nuclear Regulatory Research at the U.S. Nuclear Regulatory Commission. SAPHIRE is an integrated PRA software tool that gives a user the ability to create and analyze fault trees and event trees.

SAPHIRE contains several features:

- PC-based fault tree and event tree graphical and text editors Cut set generation and quantification
- Importance measures and uncertainty modules
- Relational database with cross-referencing features
- External events analysis (e.g., seismic, location transformation) Rule-based recovery and end-state analysis
- Common Cause Failure basic event capabilities

SAPHIRE can be used to model a complex system's response to initiating events and quantify associated consequential outcome frequencies (or probabilities). Specifically, for nuclear power plant applications, SAPHIRE 8 can identify important contributors to core damage and containment failure during a severe accident which leads to releases. It can be used for a PRA where the reactor is at full power, low power, or at shutdown conditions. SAPHIRE 8 has special features helpful for seismic PSA, e.g. [37]:

- the Histogram option allows the analyst to create histograms that can be used as uncertainty distributions for components that may not have a continuous distribution. This is where the site histogram is created to be used for the project when performing seismic analysis;
- For each failure model input, an associated uncertainty distribution can be defined. One of the predefined distribution type for uncertainty analysis is seismic lognormal;
- Two special calculation types for basic events to be treated as a seismic event. For calculation type G the probability value for screening will be calculated using the “screening G-level” (ground acceleration) and median failure acceleration (fragility) specified by the user. For calculation type G the probability value for screening will be calculated using the highest G-level (ground acceleration) from the project's “seismic hazard curve” and median failure acceleration (fragility) specified by the user.

5 Technical requirements and specifications to new seismic PSA tool

5.1 Discretisation process

The discretisation process should allow to consider the different fragility levels, and provide practical means to help analysis apply the discretisation given external data.

5.2 Uncertainties

For considering uncertainties the tool has to ensure the following specifications:

- Data uncertainties have to be included by assigning probability density functions (pdfs) 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.

In seismic PRA, 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.

5.3 Computation

The computation of Seismic PSA models is not straightforward and should consider an accurate treatment of the following aspects:

- **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.
- **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 times.

5.4 Dependencies

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.

5.5 CCF beyond 4 and 8

In the OPSAMEF format, there are 4 types of CCF models that are available, Alpha factor, Beta Factor, Multiple Greek Letters and Phi[11]. The question of dealing with non standard CCFs is not straightforward and need a development of sound methodologies. Their representation in the OPSAMEF have to be considered in a declarative way. But, 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 threre 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.

---

[11] The phi-factor model is the same as MGL and alpha-factor models except that factors for each level are given directly.

$$Q_k = \Phi_k Q$$

where, the sum of the Φ's should equal 1.

5.6 Non Rare events considerations

Considering non rare events is not in the scope of the OPSAMEF extension, and should be considered in the development of the quantification tool, which is SCRAM in the METIS project. However, there may be additional attributes that can be added in the implementation of the formalism in PSA tools, for instance, 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.

6 Extension and implementation in OPSAMEF

The modifications of the OPSAMEF proposed above aim 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.

It is thus proposed the following extensions to the OPSAMEF to consider seismic events (or other hazards) in a very effective manner:

- 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 MCS or BDD generated is suitable to assess the risk when the probability of SSC failure is closed 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 SSC 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 that takes into account the correlation between SSC failures discussed in § 3.4 and § 3.5. Any heavy modification of the PSA software is then required to handle all the possible mathematical laws used to correlate the SSC failure probability to the level of seismic hazard.

7 Implementation in Andromeda

Two approaches are considered for the implementation of the SPSA needs in Andromeda; a “Specific Approach”, which embeds seismic specific elements into the PSA domain while the second “Generic Approach”, uses generic (non seismic specific) expressions for this purpose.

7.1 Specific approach

The specific approach targets at introducing new model elements or at extending existing ones of the PSA model domain in order to obtain seismic modeling. The advantage is the simplicity of the approach. As it is possible to auto-generate corresponding APIs and other artifacts from AMF domain specifications, this approach would simply require to alter the domain specification of PSA models and to regenerate APIs. The problem with this approach is that it is not coherent with the Andromeda philosophy regarding modularity and extensibility.

7.2 Generic approach

The generic approach targets at introducing generic elements into the existing AMF domain for PSA models (or even at a lower level). The generic elements could serve to represent seismic information by the means of generic expressions (that are themselves non seismic specific e.g. attributes). Figure 2 precises the idea of introducing generic elements into the PSA domain.

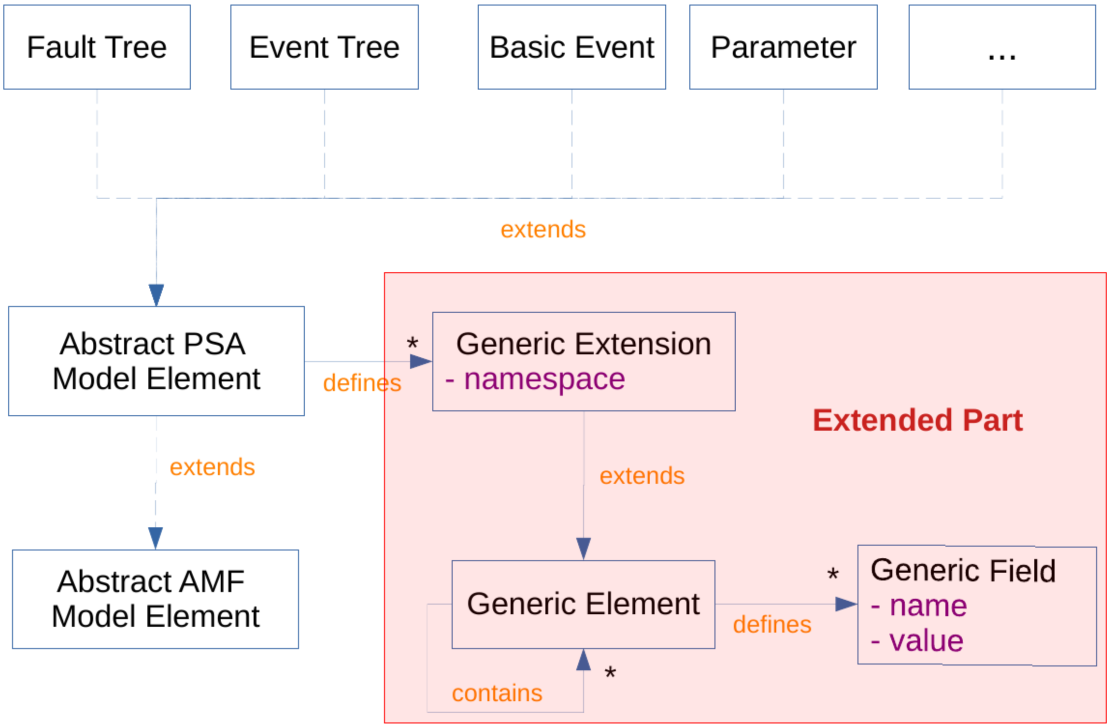

Figure 2: Generic extension of the PSA domain with seismic modeling

7.3 UI extensions

For the sake of simplicity, Andromed dedicated SPSA application should have similar modeling and quantification interfaces as in the main PSA framework. The following aspects should be considered:

- UI edition dialogs have to be extended to integrate seismic related modeling.
- Wiki (documentation) generation have to be extended to display seismic information.
- SPSA quantification engine should be integrated the new Andromeda GUI.
- Note that for this project SCRAM is the target, therefore the analysis cases have to be written according to SCRAM-NG specifications. Figure 3 shows the main steps of the quantification pipeline of SPSA models (cf. [10]).

7.4 Additional scripts for data preparation

The main aspects regarding data preparation for hazard analysis in SPSA can be done using the scripting Application Programming interface API of Andromeda (or any other tool the user may choose).

In Andromeda, Python scripts can be defined to all the calculation steps for the preparation of hazard data (fragilities or hazard frequencies see appendix A), in addition to their integration in the

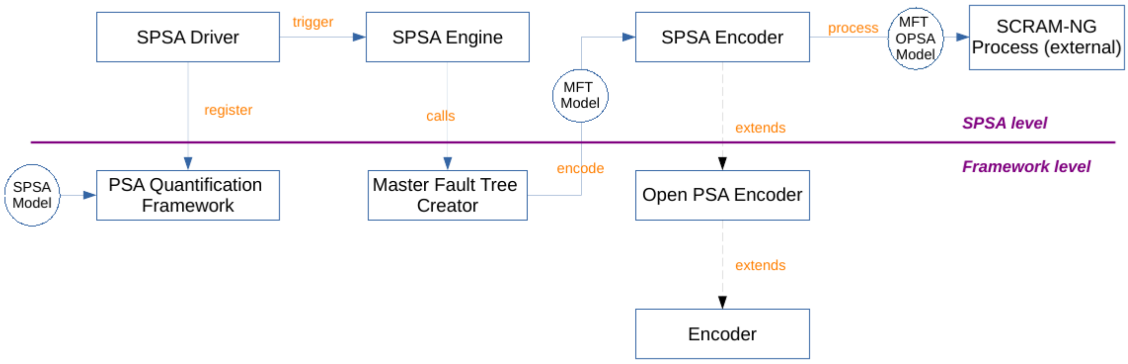

Figure 3: Overview of the main steps of the quantification pipeline of SPSA models

model in an efficient way. We point out that one of the main advantages of using such scripts is the semantics that are used to check if objects are well defined. No change can be applied without meeting the semantic constraints of the OPEN PSA grammar.

7.5 Interaction between Andromeda SCRAM and the seismic database developed in the WP7.2

The Seismic Data Base (SDB) developed in the Work Package 7.2 allows to express the relation through mathematical laws between the Systems Structures and Components (SSC) failure probability and upstream parameters used in these laws (like PGA level for example). This SDB is design 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 SPSA 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 all the spectrum of seismic levels in a continuous manner.

The modifications of the OPSAMEF format proposed in §6 are designed to allow the coupling of this SDB from WP7.2 with Amdromeda / SCRAM software.

8 Conclusion

In this report, we presented a short review of the main SPSA issues that have to be considered for an extension of OPSAMEF to deal accurately with modeling seismic events in an SPSA. We presented a number of new requirements to consider in the format but also some propositions to process the required data prior to its integration in the SPSA model.

There are two main types of issues, one is related to the way seismic data is introduced in the model. The other is related to the problems that seismic specific characteristics may introduce and that have to be solved during the quantification process.

We proposed an implementation of the extension in a variant of OPSAMEF used by the Andromeda Software (with import/export routines to OPSAMEF). Andromeda is dedicated not only to include PSA projects, but can also help preparing and processing the data from fragility and hazard curves to the computation of basic event probability/frequency through the right parameters.

References

[1] Rg-1.200 an approach for determining the technical adequacy of probabilistic risk assessment results for risk-informed activities. Technical report, U.S. Nuclear Regu latory Commission, 2009.

[2] Practical Guidance on the Use of Probabilistic Risk Assessment in Risk-Informed Applications with a Focus on the Treatment of Uncertainty. Technical report, EPRI, Palo Alto, 2012.

[3] Riskspectrum Hazard Lite User's Guide, 2013.

[4] DRESDEN nuclear power station (DRE) units 2 and 3 seismic probabilistic risk assessment in response TO 50.54 (F) letter with regard to NTTF 2.1 Seismic, dated October 2019 TO NTTF 2.1 SEISMIC. Technical report, Excellon Generation Company, 2019.

[5] Ola Bäckström and Daniel Ying. A presentation of the MCS BDD algorithm in the risk spectrum software package. In *9th International Conference on Probabilistic Safety Assessment and Management 2008, PSAM 2008*, 2008.

[6] Ken Canavan and Jeff Riley. Advanced quantification methods applied to seismic risk assessment. In *International Topical Meeting on Probabilistic Safety Assessment and Analysis 2011, PSA 2011*, 2011.

[7] E. Clement, A. Rauzy, and T. Thomas. Arbre Analyste : un outil d'arbres de défaillances respectant le standard Open-PSA et utilisant le moteur XFTA. 2015.

[8] P.E. Dr. Charles R. Scawthorn, S.E., Ronald O. Hamburger, S.E. William M. Bruin. Earthquake Risk Management: A Toolkit For Decision-Makers. Technical report, California Seismic Commission, 1999.

[9] M. Drouin, A. Gilbertson, G. Parry, J. Lehner, G. Martinez-Guridi, J. LaChance, and T. Wheeler4. Guidance on the Treatment of Uncertainties Associated with PRAs in Risk-Informed Decision-making, Final Report (NUREG-1855, Revision 1). Technical report, Office of Nuclear Regulatory Research U.S. Nuclear Regulatory Commission.

[10] Edgemind. Proposal for dealing with seismic PSA models in Andromeda. 2021.

[11] EPRI. FTREX User Manual Version 1.4, 2008.

[12] CA:2009 EPRI Palo Alto. ACUBE Software Manual.

[13] Steve Epstein, Antoine Rauzy, and Don Wakefield. Can we trust PRA: Take 3. In *Proceedings of the 8th International Conference on Probabilistic Safety Assessment and Management, PSAM 2006.* IAPSAM, 2006.

[14] Epstein S, Reinhart M.F. & Rauzy A. Validation Project for the Open-PSA Model Exchange using RiskSpectrum and CAFTA. In *Proc. of the 10th International Probability assessment and Management Conference*, Seattle, 2010.

[15] Thomas Friedlhuber. *Model Engineering in a mudular PSA.* PhD thesis, Ecole Polytechnique, 2014.

[16] Thomas Friedlhuber, Mohamed Hibti, and Antoine Rauzy. Overview of the open PSA platform. In *11th International Probabilistic Safety Assessment and Management Conference and the Annual European Safety and Reliability Conference 2012, PSAM11 ESREL 2012*, 2012.

[17] Sang Hoon Han, Ho Gon Lim, Seung Cheol Jang, and Joon Eon Yang. AIMS-PSA: A software for integrated PSA. In *PSAM 2016 - 13th International Conference on Probabilistic Safety Assessment and Management*, 2017.

[18] Laurent Hyafil and Ronald L. Rivest. Constructing optimal binary decision trees is NP-complete. *Information Processing Letters*, 1976.

[19] Woo Sik Jung. A method to improve cutset probability calculation in probabilistic safety assessment of nuclear power plants. *Reliability Engineering and System Safety*, 2015.

[20] Woo Sik Jung, Kevin Hwang, and Seong Kyu Park. A new methodology for modeling explicit seismic common cause failures for seismic multi-unit probabilistic safety assessment. *Nuclear Engineering and Technology*, 2020.

[21] Annie M. Kammerer and Jon P. Ake. Nureg 2217 - practical implementation guidelines for SSHAC level 3 and 4 hazard studies. Technical report, U.S. Nuclear Regulatory Commission, 2012.

[22] Stan Kaplan and James C Lin. An Improved Condensation Procedure in Discrete Probability Distribution Calculations. *Risk Analysis*, 7(1):15–19, 1987.

[23] Stanley Kaplan. On The Method of Discrete Probability Distributions in Risk and Reliability Calculations–Application to Seismic Risk Assessment. *Risk Analysis*, 1(3):189–196, 1981.

[24] Jung Han Kim, In-Kil Choi, Min Kyu Kim, Sang-Hoon Han, and Jin-Hee Park. Development of advanced seismic PSA software, PRASSE.

[25] Min Kyu Kim, Young Sun Choun, In Kil Choi, and Yasuki Ohtori. An Improved Seismic PRA Method for a Korean NPP Site.

[26] F. L. Leverenz and H. Kirch. User's Guide for the WAM-BAM Computer Code. Technical report, EPRI, 1976.

[27] Nikolaos E. Limnios and Rezki Ziani. Algorithm for reducing cut sets in fault-tree analysis. *IEEE Transactions on Reliability*, 1986.

[28] Andrea Maioli, Martin W. McCann, and David J. Finnicum. Seismic PRA modeling and quantification approaches. In *International Topical Meeting on Probabilistic Safety Assessment and Analysis 2011, PSA 2011*, 2011.

[29] Tetsukuni Oikawa, Masaaki Kondo, Yoshinobu Mizuno, Yuichi Watanabe, Hiroshi Fukuoka, and Ken Muramatsu. Development of systems reliability analysis code SECOM-2 for seismic PSA. *Reliability Engineering & System Safety*, 62(3):251–271, 1998.

[30] R. J. Budnitz, G. S. Hardy, D. L. Moore, and M.K. Ravindra. *Correlation of Seismic Performance in Similar SSCs (Structures, Systems, and Components)*. Number December 2017. United States Nuclear Regulatory Commission, Office of Nuclear Regulatory Research, 2017.

[31] Lavinia Raganeli. *A Study of methods for including uncertainty in Seismic PSA*. Phd thesis, Imperial College London, 2019.

[32] Lavinia Raganelli and Keith Ardron. A method for inclusion of uncertainties in seismic PSA. In *PSAM 2018 - Probabilistic Safety Assessment and Management*, 2018.

[33] Olzhas Rakhimov. SCRAM.

[34] Martin Richner, Sener Tinic, Mayasandra Ravindra, Beigi Campbell, Robert Farzin, and Asfura Alejandro. Insights gained from the beznau seismic psa including level 2 considerations. In *ANS PSA 2008 Topical Meeting - Challenges to PSA during the nuclear renaissance*, 2008.

[35] Junghyun Ryu and Moosung Jae. A quantification methodology of Seismic Probabilistic Safety Assessment for nuclear power plant. *Annals of Nuclear Energy*, 2021.

[36] Oleksandr Sevbo. Definition and classification scheme of SSCs for specific and generic seismic fragility evaluation. Technical report, METIS WP6, D6.1, 2021.

[37] Curtis Smith, James Knudsen, Kurt Vedros, Michael Michael, Kellie Kvarfordt, and Ted Wood. SAPHIRE 8 Basics An Introduction to Probabilistic Risk Assessment via the Systems Analysis Program for Hands-On Integrated Reliability Evaluations (SAPHIRE) Software P-201, 2016.

[38] Simone SULLIVAN and Sylvain BOULLEY. End users survey and exploitation of results. Technical report, METIS - EDF Energy, 2021.

[39] Doug True, Edward T. Burns, and Kenneth Canavan. Guidelines for the treatment of uncertainty in risk-informed regulatory applications. In *American Nuclear Society International Topical Meeting on Probabilistic Safety Analysis, PSA 05*, 2005.

[40] D. E. Vanover, E. T. Burns, True D. E., J. Primet, and A. M. Bonnevialle. Guideline for the Treatment of Uncertainty in Risk-Informed Applications: Applications Guide. Technical report, EPRI, 2006.

[41] Swetha Veeraraghavan, Chandrakanth Bolisetti, Andrew Slaughter, Justin Coleman, Somayajulu Dhulipala, William Hoffman, Kyungtae Kim, Efe Kurt, Robert Spears, and Lynn Munday. MASTODON: An Open-Source Software for Seismic Analysis and Risk Assessment of Critical Infrastructure. *Nuclear Technology*, 207(7):1073–1095, 2021.

[42] Yican Wu. Development of reliability and probabilistic safety assessment program RiskA. *Annals of Nuclear Energy*, 2015.

A Seismic Calculations

In this appendix[12] we present some of the functions in HazardLite (cf. [3]) that can be used directly to produce seismic data or either implement in Andromeda:

- Hazard curves are divided into discrete intervals **by the analyst**.
- Within each interval HazardLite will generate the hazard frequency and the fragility. The basic events are intended to be used as initiators (frequency) and as failures (basic events).
- Fragilities may be grouped and combined (Combinations may be relevant when several fragility events are found in the same MCS.)
- Each of the defined intervals are subdivided into a number of sub-intervals. The chosen amount of subintervals is 100 in HazardLite.
- Within each interval the hazard frequency, as well as the fragility for each component is calculated. The calculation of the fragility is convoluted with the frequency, to account for differences in the interval (both the hazard curves and the fragility curve will change value within the interval).

  More details can be found in [3], we only present a summary of the computations that are used.

A.1 Quantification of the hazard frequency

For each interval, the frequency of occurrence (FoO) is calculated as the difference between the upped and lower bounds of the frequencies at the interval ends.

$$FoO^i = FoO^i_{up} - FoO^i_{low}$$

If many curves are used, the weighted mean is calculated and the same formula apply.

A.2 Fragility computation

The mean fragility curve is considered. In the point estimate calculation there are two main methods

Simplified for each interval, the fragility is calculated based on the representative *Peak Ground Acceleration* (PGA) for the interval.

$$a^i_{pg} = \frac{a^i_{pg,lower} + a^i_{pg,upper}}{2} \tag{1}$$

(mean acceleration)
Given a^i_{pg} The mean fragility associated with interval i is then given by

$$f' = P^i_{def,X}(a^i_{pg}) = \Phi\left[\frac{ln(\frac{a^i_{pg}}{A_m})}{\beta_C}\right] \tag{2}$$

where $\beta_C = \sqrt{\beta_R^2 + \beta_U^2}$

Convolution product for each interval, the fragility is calculated not on a representative PGA of the interval but by a convolution on the PGA's over all the interval.

$$F_{i,h_k} = \frac{\sum_{j=1}^{100}(h_{i,j} \times f_{i,j})}{\sum_{j=1}^{100}(h_{i,j}} \tag{3}$$

where

---

[12] This appendix may disappear in the final version.

- F_{i,h_k} is the fragility calculated for the interval i following the hazard curve k.
- $h_{i,j}$ is the frequency occurrence for the interval i and the sub-interval j.
- $f_{i,j}$ the fragility calculated for the interval i and the sub-interval j.

Calculation of fragility for group of events Where many hazard curves are considered, the fragility of a component is calculated by:

$$F_i = \sum_{k=1}^{n} F_{i,h_k} \times W_{h_k} \tag{4}$$

where

- W_{h_k} is the weight associated with the hazard curve k
- F_{i,h_k} is the fragility calculated for the interval i given the hazard curve k.

Calculation of fragility for combination of events In a group, the fragility of a group of components is defined as

$$F_{group} = 1 - \prod_{i\in 1}^{n}(1 - F_i) \tag{5}$$

i refers to the intervals index (assuming the independence of the events of the group).

$$F_{group} = \frac{\sum_{k=1}^{100}\left[1 - \prod_{j\in 1}^{n}(1 - F_{j,h_k}.h_k)\right]}{\sum_{k=1}^{100} h_k} \tag{6}$$

where

- F_{i,h_k} is the fragility calculated for the component j and the sub-interval k.
- h_k is the occurrence frequency of the hazard in the sub-interval k.

A.3 Uncertainty calculation

The same approach apply for the uncertainty calculation, but instead of using mean values, sampling is done over all the values.

The algorithm used by HazardLite [3] is the following.

1. Randomly select one of the hazard curves (according to its weight)
2. Randomly select one of the fragility curves in the group of fragility curves (for each component)
3. Calculate the hazard frequencies for all defined intervals
4. Calculate the fragilities for all intervals, under the condition of the selected hazard curve (convolute with the selected hazard curve only)
5. Calculate Component groups and combinations
6. Perform next sampling

Index

Acceleration, 8
Acceleration
  fixed, 9
ACUBE, 11–13
Advanced Min Cut Upper Bound Estimator (ACUBE), 11
AIMS-PSA, 15
Andromeda, 17, 19

BDD, 17
BDD
  Optimal, 6
Binary decision diagram (BDD), 6
Boolean reduction, 6
Buckling, 8

C-BDD, 12
CAFTA, 13
CCF, 16
Common Cause Failures (CCF), 6
Compatibility, 7
Conditional probability, 7, 16
Contact, 8
Core Damage Frequency (CDF), 8
Curve
  Fragility, 7
Cutsets, 6

Data base, 19
Delete term, 17

Earthquake intensity, 9
End-states, 7
EQESRA, 14
events
  Non rare, 6

Fixed
  Acceleration, 9
Fragility, 6
Fragility curve, 7
Frequency
  Return, 7

HazardLite, 12

Ignore success branches, 17

Master Fault Tree (MFT), 6
MASTODON, 14
Maximal number of nodes, 12
MCS, 17
MCS BDD, 13
MCS Limit, 12
METIS, 6
Min Cut Upper Bound, 11
Min Cut Upper Bound (MCUB), 13
Monte Carlo method, 8
MOOSE, 14

Non rare events, 6
Non-linearity, 8
NP-Complete, 6
NRC, 9
Nuclear Regulatory Commission (NRC), 9

Open PSA Exchange Format, 7
OPSAMEF, 7, 17
Optimal BDD, 6

Peak Ground Acceleration (PGA), 23
PGA, 23
Pivot Q and FV Limits, 12
Portability, 7
PRASSE, 14
Prime implicants, 6
Probability density function, 7

Quality assurance, 7

Random phasing, 8
Rare Event Approximation (RAE), 8
Return frequency, 7
Riskspectrum, 12
Riskspectrum
  HazardLite, 12

SAPHIRE, 15
SCDF, 13
SCRAM, 17, 19
SECOM-2, 14
Seismic
  Fragility, 6
Seismic Data Base (SDB), 19
Seismic Initiating Event Tree, 6
Seismic load, 7
Seismic load intensity, 16
Siding, 8
SIET, 6
SLERF, 13
SSC, 6

Structures, Systems and Components, 6

Type Code database, 13

Uncert, 13
US Nuclear Regulatory Commission (NRC), 9

Wam-Bam computer code, 14