NARSIS

New Approach to Reactor Safety ImprovementS

WP1: Characterization of potential physical threats due to different external hazards and scenarios

D1.9: Recommendations for regulators using the integrated hazard framework

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PU	Public	**X**
PP	Restricted to other programme participants (including the Commission Services)	
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List of Abbreviations

AEP	Annual Exceedance Probability
ASAMPSA_E	Advanced Safety Assessment Methodologies: Extended PSA
BN	Bayesian Networks
BMA	Block Maxima Approach
CMS	Conditional Mean Spectra
EVM	Extreme Value Model
GMPE	Ground Motion Prediction Equation
DSHA	Deterministic seismic hazard assessment
DTHA	Deterministic Tsunami Hazard Assessment
IAEA	International Atomic Energy Agency
MCE	Maximum Credible Earthquake
NEAM	North East Atlantic and Mediterranean
NPP	Nuclear Power Plant
NUREG	Nuclear Regulatory Commission Report
PGA	Peak Ground Acceleration
PGV	Peak Ground Velocity
POT	Peak over threshold
POI	Points of Interest
PSA	Probabilistic Safety Assessment
PSHA	Probabilistic Seismic Hazard Assessment
PTHA	Probabilistic Tsunami Hazard Assessment
SHARE	Seismic Hazard Harmonization in Europe
SSC	Structure, System, Components
SSG	Specific Safety Guide
WENRA	Western European Nuclear Regulators’ Association

1 Executive Summary

This deliverable is the last one of the Work Package 1 (WP1) of NARSIS project. It constitutes a practical synthesis of WP1, and more specifically, it aims to provide recommendations to the regulators for the application of the integrated hazard framework methodology for multi-hazard assessment, to use in the future Probabilistic Safety Assessments (PSA) of Nuclear Power Plants (NPPs).

A huge number of external hazards from natural catastrophes exist – over 70 of geophysical, meteorological, extra-terrestrial, biological, hydrological origin as determined by the ASAMPSA_E project. These hazards can occur singularly with direct or indirect impacts on NPPs or as various multi-hazard scenarios, in which these hazards either occur independently in a same time window or are correlated, with different types of interactions between them.

This deliverable presents, describes and provides recommendations for the application of the multi-hazard assessment framework developed in Work Package 1 of NARSIS project. The proposed methodology is based on the MATRIX approach, from Liu and al. (2015), with complements and adaptations for the NPP specific nature. The framework includes five successive levels:

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

In the multi-hazard scenarios, two specific concepts are taken into account: the potential relationship between two hazards (one may trigger or contribute to cause another one) and the time laps between the occurrences of hazards that may induce cumulative damages (concept of time-variant vulnerability).

To apply the Level 0 of the framework, a focus is made on hazard characterisation methods, and in particular for four natural hazards: earthquakes, tsunamis, extreme weathers and flooding. The current practice and some advanced methods are presented.

The successive levels of the framework are then detailed. The identification of all possible multi-hazard scenarios is the first goal of the developed methodology. Another important goal is to provide quantitative assessment of each scenario, in terms of probability of occurrence, and when possible, in terms of the effects caused on the main components of the NPPs, taking into account the design provisions adopted against the respective hazard. A last goal is to qualify and quantify the uncertainty all along the methodology and in the results.

Uncertainty forms a major part of any result, given the large variability of events, the quantity and reliability of datasets (epistemic uncertainty) and simply the random nature of natural hazards (aleatory variability). Uncertainty quantification has to be taken into account at each step of the framework, from the hazard source to the site effects. Uncertainty quantification is particularly relevant whenever historical data are extrapolated in order to derive statements about return periods that are far longer than historical records..

2 Background and Introduction

2.1 Scope, Objectives and Organisation of the Deliverable

This deliverable is the last one of the Work Package 1 (WP1) of NARSIS project. The topic of WP1 is to propose new approaches for characterization of potential physical threats to a nuclear installation, due to different external natural multi-hazards occurring independently or with interaction between them.

WP1 includes nine deliverables, D1.1 to D1.9, organised as illustrated below on Figure 1.

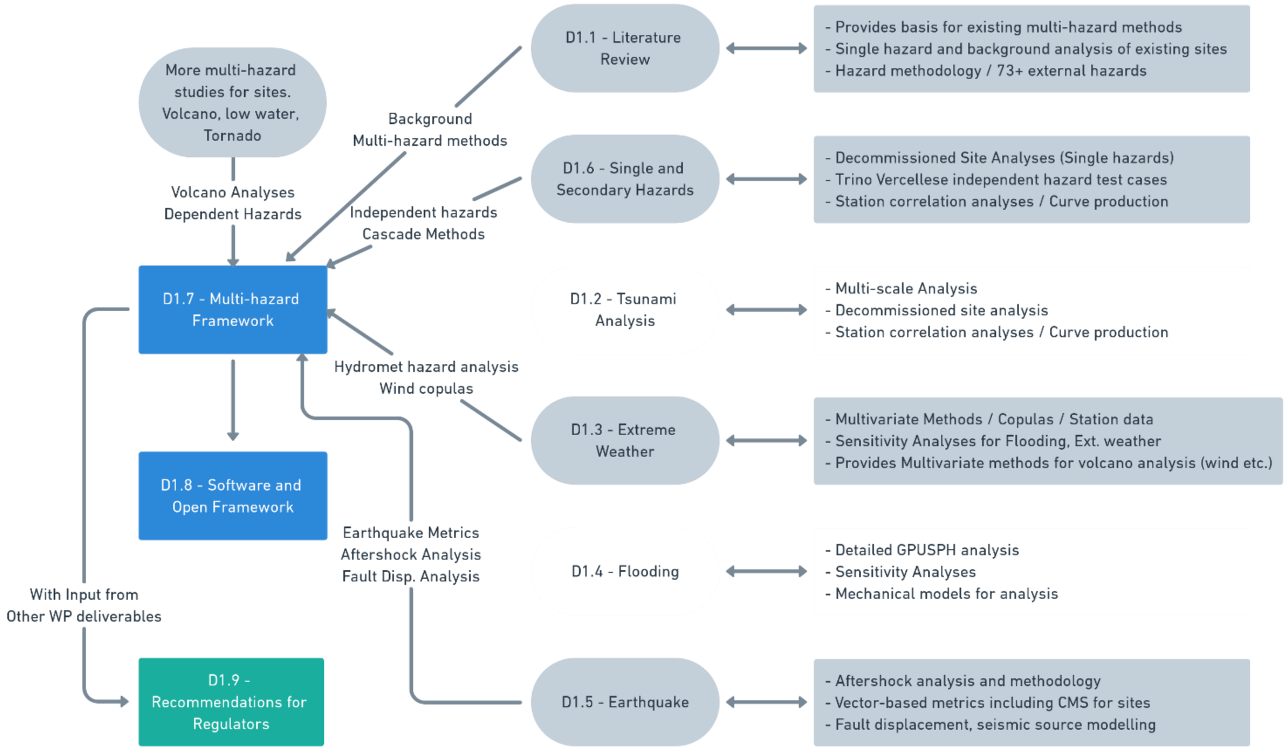


Figure 1: Organisation of deliverables in NARSIS WP1

The present deliverable (D1.9) constitutes a practical synthesis of WP1, and more specifically, it aims to provide recommendations to the regulators for the application of the integrated hazard framework methodology for multi-hazard assessment, to use in the future Probabilistic Safety Assessment (PSA) procedures for Nuclear Power Plants (NPP).

A huge number of external hazards from natural catastrophes exist – over 70 of geophysical, meteorological, extra-terrestrial, biological, hydrological origin as determined by the ASAMPSA_E project. These hazards can occur singularly with direct or indirect impacts on NPPs or as various multi-hazard scenarios, in which these hazards or their consequences either occur independently in a same time window or are correlated, with different types of interactions between them. Certain

This deliverable presents and describes the multi-hazard assessment framework and the proposed methodology based on the MATRIX approach (Liu and al., 2015), with complements and adaptations for the NPP specific nature.

The scope and objectives of this deliverable are to describe the main steps of the methodology to the regulators. The identification of all possible multi-hazard scenarios is the first goal of the developed methodology presented in this document. Another important goal is to provide quantitative assessment of each scenario, in terms of probability of occurrence, and when possible, in terms of the effects caused on the main components of the NPPs. A last goal is to qualify and quantify the uncertainty all along the methodology and in the results.

The previous WP1 deliverables have explored in detail the different stages of the methodology, from the individual hazard characterisation (D1.1 to D1.6) to the final quantitative assessment of the multi-hazard scenario (D1.7). Even if the method presented in this document is to be applied for new and existing power plants, it is worth to notice that the method presented in this document has been tested, discussed and validated on some decommissioned nuclear sites across Europe (D1.6 and D1.7).

To summarize, the scope of D1.9 includes:

- The definition of the key concepts of a multi-hazard assessment: hazard characterisation, interrelation between hazards, time window and overlapping of event consequences;
- The description of the successive steps of the new integrated hazard framework for a multi-hazard assessment of NPPs;
- Some conclusions and considerations about the limits of the methods, the uncertainty assessment, and the interactions with the other Work Packages (WP2: vulnerability analysis and WP3: integration and safety analysis).

This deliverable, as others of WP1 **only** (*), takes into account scenarios composed of natural external hazards. The interactions with internal hazards in the plant can be incorporated within the methodology; however, the propagation of uncertainty needs much further study with regards to multi-hazard methodologies as well as the application within PSA.

(*) "Only" is important because the link between an external hazard and an internal one could occur and are treated as follows: either the internal hazard is induced by the external one, in which case it is analyzed in the context of the PSA associated with the external hazard (for example the seismic PSA addresses the risk of fire induced by an earthquake); either the two hazards are independent, in which case the occurrence of this combination will present a low or even residual frequency and de facto there is little safety issue to develop this PSA.

The deliverable is organised as follows:

- Section 3 develops the general background and overview of the multi-hazard assessment, the main improvements brought by the integrated hazard framework, compared to the current practice of multi-hazard assessments in the PSA.
- Section 4 provides the main definitions and key concepts used in the proposed integrated hazard framework to avoid any confusion or misunderstanding.
- Section 5 exposes the five successive levels of the new integrated hazard assessment.
- Section 6 summarizes the key aspects for the implementation, considerations on the assessment of uncertainties and limits of the methodology.

2.2 Existing Guidance: Key Documents

There exist a large number of documents, which are key reading for the understanding of the basis and the background of the NARSIS multi-hazard integration framework, as part of extended PSAs and hazard assessments in general:

- The ASAMPSA_E deliverables (www.asampsa-e.eu/deliverables-library): they are seen as important and can be examined as part of the previous deliverables;
- International and national standards, including various IAEA reports (https://www.iaea.org/publications).
- The WENRA documentation also provides an important basis for the work within this deliverable (https://www.wenra.eu/publications).
- The MATRIX project deliverables (Multi-HAzard and MulTi-RIsK Assessment MethodS for Europe).
- The NARSIS project deliverables (http://www.narsis.eu/page/deliverables)

3 Background of multi-hazard assessment

According to the IAEA Specific Safety Guide SSG-3 (2010), the Level 1 - PSA shall consider single as well as combined external hazards.

Until now, expert judgement is used to identify the probability of different extreme hazard combinations, for instance adopting a matrix method with expert panel aimed on identification of critical combinations for a given plant design. Relevant combinations are site specific and their identification remains a challenging and laborious task. Knowledgeable personnel at the site, available historical information and reasonable known physical phenomena should inform it. Additionally, the identification of hazards is based on conventional design codes that contain relevant information in terms of hazard maps. Example: seismic zonation in Eurocode 8 Part 1.

In view of the Fukushima-Daiichi accident induced by the Tohoku earthquake and the consecutive tsunami in 2011, the existing PSAs for NPPs manifest specific insufficiencies about the identification of rare events, their combinations and the assessment of their consequences. Since this accident, improved methodologies of multi-hazard scenarios assessments have been developed. The NARSIS project pointed out the necessity of upgrading the current methodological framework such as cascading and/or conjunct events characterization, structure responses and uncertainties treatment.

Figure 2 shows the difference between the single hazard and multi-hazard approaches. In scenarios of single hazards, the extreme events may occur successively in the lifetime of the NPP without any spatial or temporal interaction. In the multi-hazard scenarios, two specific concepts are taken into account: the potential relationship between two hazards (one may trigger or contribute to cause another one) and the time laps between the occurrences of hazards that may induce cumulative damages (concept of time-variant vulnerability). Generally, time steps would be less than 72 hours for these interactions when damage has occurred given that operational procedures would be implemented. Recovery data is difficult to take into account in practice as shown in Figure 2. When limited damage or no damage from the initial hazard occurs, then shut down may not be implemented and interactions on the hazard and vulnerability side may occur at longer time steps (>72 hours).

To provide practical solutions to the IAEA requirement of including all realistic scenarios of combined hazards in PSA, a multi-hazard assessment framework has been developed in the Work Package 1 of the NARSIS project. The framework is built upon the work of the MATRIX project, as well as a number of insights from other EU projects such as ASAMPSA_E for single hazards identification.

The objectives of this new integrated hazard framework are the following:

- identify and consider all possible scenarios inducing physical threats on NPPs: these scenarios must include combinations of independent events, occurring in a specified time window as well as dependent events with any possible type of interrelation between them.
- take into account the specific vulnerability of relevant NPP components, and their time of recovery in case of damages. This means that the vulnerability analysis of NPP component is relevant at the stage of hazard assessment.
- make a quantitative assessment of the probability of occurrence of the identified scenarios, in terms of the quantity of interest (intensity measure) that is representing a hazard to SSCs of the NPP .

Uncertainty forms a major part of any result, given the large variability of events, the quantity and reliability of datasets (epistemic uncertainty) and simply the random nature of natural hazards (aleatory variability). Uncertainty quantification has to be taken into account at each step of the framework, from the hazard source to the site effects. Uncertainty quantification is particularly relevant whenever historical data are extrapolated in order to derive statements about return periods that are far longer than historical records.

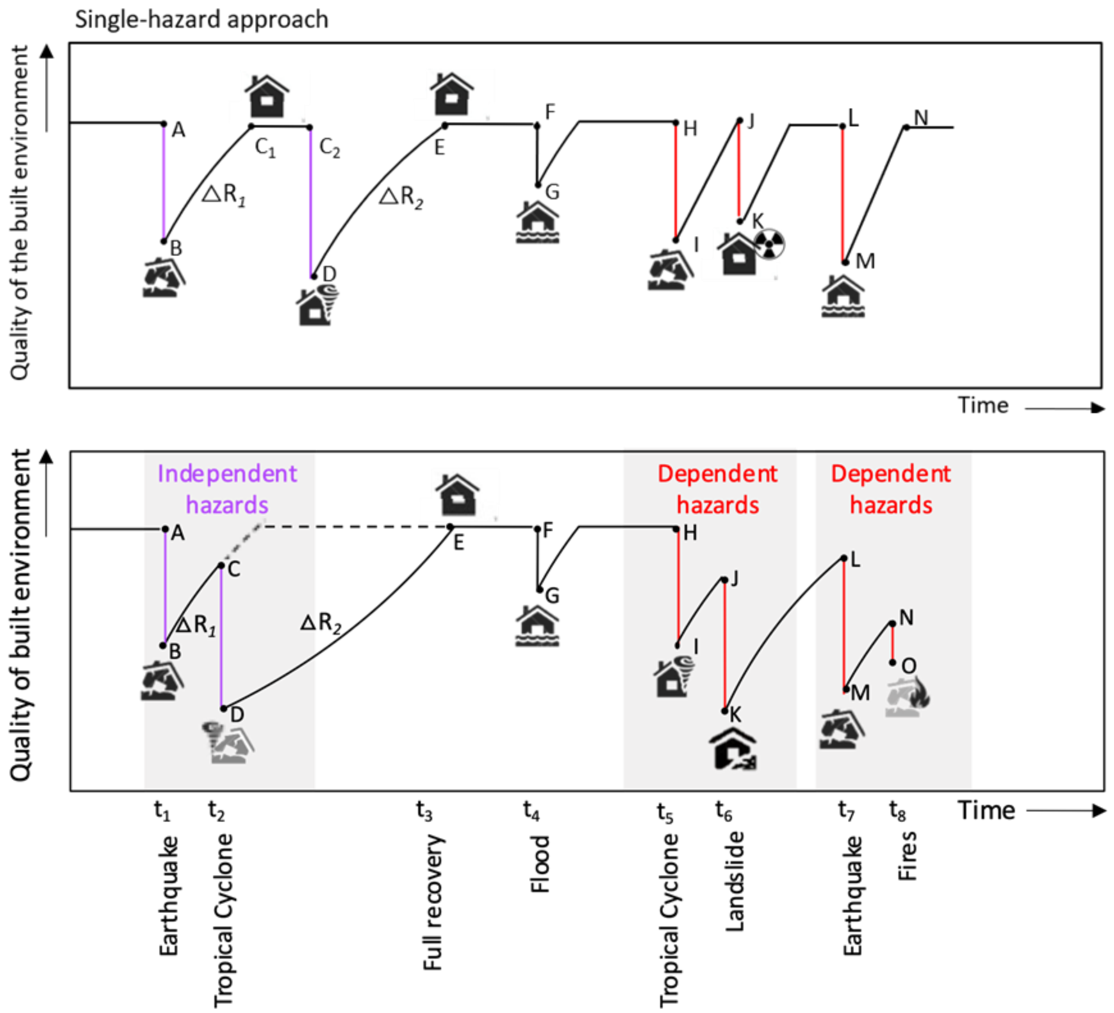


Figure 2: Schematic representation of the single- and multi-hazard temporal patterns and the recovery of independent and dependent hazard types (de Ruiter et al., 2020)

4 Main terms and concepts used in the Integrated Hazard Framework for multi-hazard assessment

Different terms and concepts are used in the following integrated hazard framework methodology. To avoid any confusion or misunderstanding, the following list provides their definition.

Hazard: An event or a natural phenomenon that poses some risk to a facility.

Natural hazard: Those hazards which occur in nature over which man has little or no control over the magnitude or frequency.

External hazard: Hazard originating from sources located outside the site area of the nuclear power plant (IAEA SSG-3, 2010). External hazard do not often affect the plant itself, but also affects roads, infrastructure, utility links and other infrastructure surrounding the plant as well as the human operatives within and outside the plant.

Regarding the external natural hazards susceptible to impact a nuclear power plant, the current deliverable adopts the extensive list provided in the ASAMPSA_E – D21.2 document (73 hazards of geophysical, meteorological, extra-terrestrial, biological, hydrological origin), and the format of the hazard list published in the IAEA Safety standard (SSG-3, annex I).

Hazard characterisation: The process to determine an estimate of the expected frequency of exceedance (over some specified time interval) of various levels of some characteristic measures of the intensity of a hazard (key metrics).

Hazard characterisation methods: To characterise natural hazards, two main approaches are used:

- **Statistical approaches** are based on past phenomena to establish probability of occurrence for these same events in the future. These approaches relate a hazard level or intensity to a given return period.
- **Deterministic approaches** give a hazard level based on (generally) a worst-case scenario. They include naturalistic methods of the physical study of the phenomenon.

Statistical methods enable quantitative evaluation of the hazard for a given occurrence, whereas naturalistic methods are primarily quantitative. Therefore, statistical methods are used more for evaluating the hazard level of natural risks.

T-year return period: The statistical interval of occurrence of a natural hazard. The concept of return period assumes stationarity of the phenomenon being studied.

Annual probability of exceedance: The probability of exceedance of a level of a key metric, for a time period of interest of 1 year. The annual exceedance probability is preferred for non-stationary hazards for it can vary from now to the future.

Hazard curve: The result of the hazard characterisation using a statistical method: the curve that plots a key metric that characterizes the given single hazard or hazard combination, versus an annual exceedance probability (AEP) or a T-year return period of occurrence.

Hazard dependency: Five different interaction types will be used in this framework.

- **Independency / Independent hazards**: when there is no dependence or triggering relationship between hazards. Occurrence of two or more independent hazards simultaneously (or in a given time window) is thus a coincidence (for example a weather-induced flood and an earthquake).
- **Triggering / cascading hazards**: when one primary hazard causes or triggers one (or more) other hazard(s), (for example an earthquake and a tsunami).
- **Change conditions hazards**: when one hazard may alter the second hazard by changing the environmental conditions (for example a bushfire altering the roughness of an area and then increasing the effects of a later flood event).

- **Compound or associated hazards**: when different hazards are the result of the same primary event or large-scale processes. This is not the same as triggering / cascading in that the primary and secondary hazards occur simultaneously (for example river flooding and sea surge caused by a typhoon).
- **Mutual exclusion or negative dependence**: when two hazards exhibit negative dependence, they cannot occur together or the occurrence of one excludes the occurrence of the other (for example bushfire and heavy rain).

Duration of event: the elapsed time from the starting of the hazard sequence to its end.

For each external hazard given in the ASAMPSA_E list, a typical duration is associated. Duration is classified into seconds to minutes (s-m), minutes to hour (m-h), hours to days (h-d), and longer (d-l).

Time window: when referring to the duration of different single event sequences. Three different time windows are defined:

- **Analysis time window**: this is the time window desired for the hazard assessment, which is typically one year; but is generally site specific.
- **Hazard event time window**: the time interval during which the hazard induced loads exist and after which they no longer cause effects which can affect a NPP. It is thus equivalent to the duration of event. The minimum, maximum and mean duration of the different hazards of the ASAMPSA_E have been assessed and are given in the Excel file Duration_Matrix_NARSIS_WP1.xls provided in NARSIS website (The information on duration is given also in report ASAMPSA_D21.2:
- http://asampsa.eu/wp-content/uploads/2014/10/ASAMPSA_E-D21.2_External_Hazard_List.pdf). These durations can be used as a guidance to the potential hazard event time window for any combination of hazards.
- **Operational time window**: the duration taken for the hazard effect to subside and the associated plant checks, damage repairs and safety procedures to occur. The operational time window is very plant specific and is determined as part of WP2-5 where the operational protocols in direct combination with the hazard impacts are examined.

Threshold for damage on a NPP component: value of a key metric that characterizes the hazard, at which the component is assumed to be disabled or malfunctioning. Conceptually, these threshold values can be derived from the design studies of the plant for the respective systems, structures and components.

Screening for correlation of external hazards (via TECDOC-1937):

Based on design basis hazard event frequency

Correlated hazards can be screened out if (a) the plant has a design basis for both hazards; (b) the plant will not directly suffer core damage if all SSCs that are not designed to either design basis hazard event fail; and (c) the frequency of the correlated design basis hazard event is less than 1% of the internal events CDF for a single reactor unit. If the hazard can affect multiple units on the site, it can be screened out if the frequency of the correlated design basis hazard events is less than 1% of seismic CDF.

Based on design basis hazard event core damage frequency

Correlated hazards can be screened out if (a) the plant has a design basis for both hazards; (b) the plant conditional core damage probability is calculated assuming all SSCs that are not designed to either design basis hazard event fail; and (c) the frequency of the correlated design basis hazard events multiplied by the conditional core damage probability is less than 1% of the internal events CDF.

Based on overall hazard frequency

Correlated hazards can be screened out if either (1) a bounding or demonstrably conservative estimate of the hazard frequency (over the full range of hazard event severity) is less than 1% of the internal events CDF, or (2) a realistic estimate of the hazard frequency (over the full range of hazard event severity) is less than 0.1% of the internal events CDF.

Based on overall core damage frequency

Correlated hazards can be screened out if a bounding or demonstrably conservative estimate of CDF (over the full range of hazard event severity) is less than 1% of the internal events CDF. It is assumed that earthquake and tsunami are identified as dominant hazards at a target site after external hazards are screened out from all potential hazards, based on a criterion established in IAEA Safety Reports Series No. 92.

5 Application of the integrated hazard framework

5.1 General overview of the methodology

The integrated hazard framework methodology developed in WP1, is an adaptation of MATRIX 3-level approach (Liu et al. 2015), at which a number of insights from other EU projects have been added.

The framework, as illustrated on Figure 3, includes five successive levels:

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

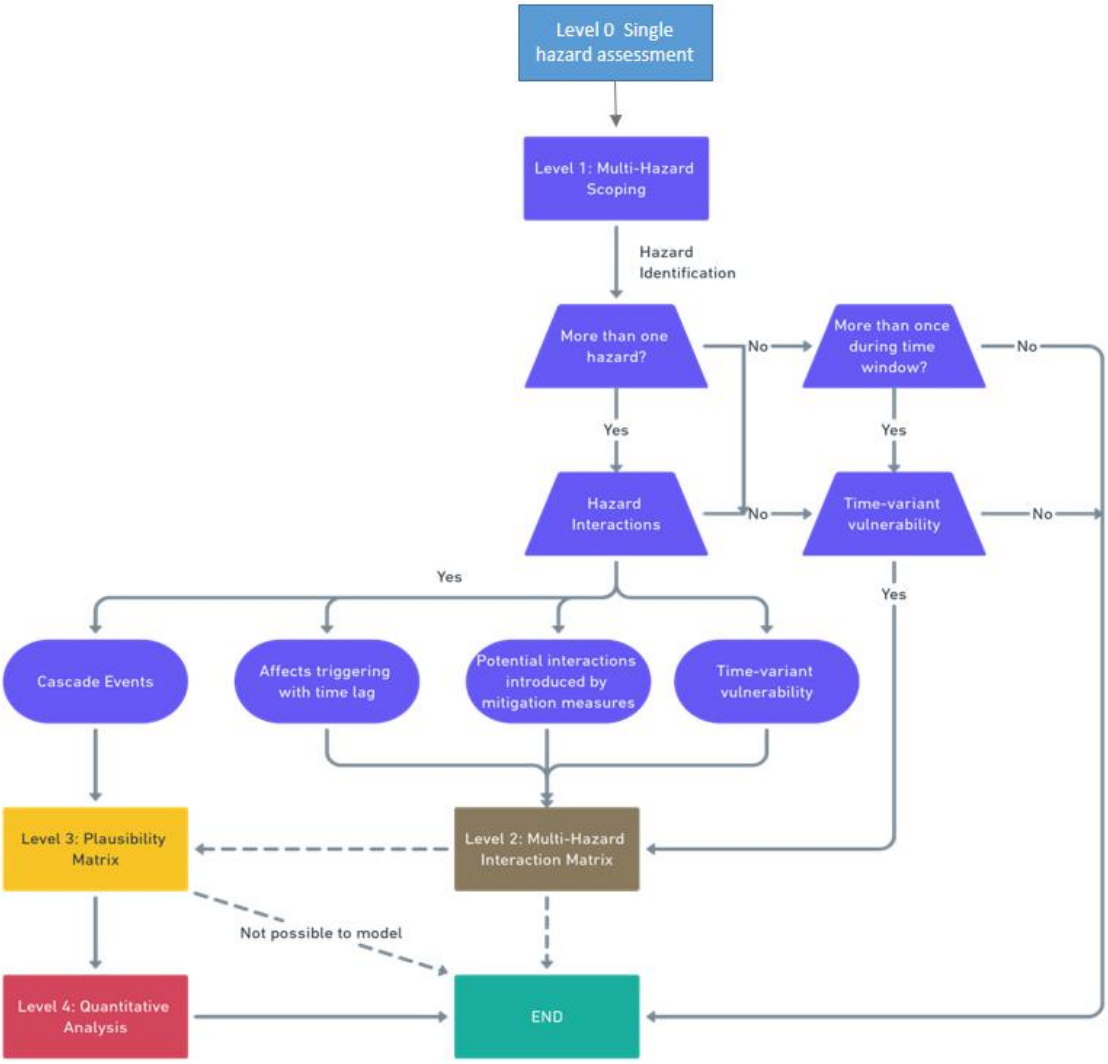


Figure 3: General flowchart of the integrated hazard framework

5.2 Level 0: single hazard assessment

The goals of the Level 0 analysis are:

- The identification of external hazards relevant for the NPP;
- The hazards characterization including: determination of event duration and probability of occurrence at the site location, given by the production of hazard curves;
- The definition of the thresholds of damage of the NPP components under the effects of these hazards.

5.2.1 Hazard identification

The identification of all external hazards relevant to the site plant is made using the ASAMPSA_E list of 73 natural hazards classified into geophysical, hydrological, meteorological, extra-terrestrial, and biological families. The hazard list is available at project website http://asampsa.eu/wp-content/uploads/2014/10/ASAMPSA_E-D21.2_External_Hazard_List.pdf. This report adopts the format of the hazard list including the following information associated to each hazard:

- Code (hazard number);
- Hazard: natural phenomena causing the hazard;
- References: international standards that introduces the hazard type;
- Duration (Dur.): classification of hazard duration. Duration is classified into seconds to minutes (s-m), minutes to hour (m-h), hours to days (h-d), and longer (d-l);
- Predictability and hazard progression (P&P): predictable (e.g. by weather forecast, P) or unpredictable (U), progressing rapidly (R) or gradually (G);
- Hazard definition and hazard impact: definition of the hazard, the main potential impacts caused on the plant and the initiating event in case the hazard is a secondary effect of another one;
- Interfaces and comments: extended explanations of some uncommon natural phenomena.

The durations of hazards are compiled in an Excel file “Duration_Matrix_NARSIS_WP1.xlsx” provided on the NARSIS website (also available in in Table 2 of report: http://asampsa.eu/wp-content/uploads/2014/10/ASAMPSA_E-D21.2_External_Hazard_List.pdf):) for each of the previous 73 external hazards, a minimum, maximum and mean durations are given. Within NARSIS these durations were reviewed and adjusted.

These durations can be used as a guidance as to the potential hazard event time windows which are present for any combination of hazards. In terms of duration determination however, the hazard type should be modelled directly as a function of magnitude and typology versus time. For primary and secondary effect combinations, this becomes more difficult with often stochastic or mechanical modelling being needed to determine the plausible hazard event time windows. This is also very dependent on site effects, basin effects and other non-linear effects. For instance, earthquake shaking may only last a few seconds on a rock site, vs. tens of seconds on a soft soil site or in a basin.

The possible secondary hazards must also be identified as part of Level 0 identification of hazards. It is advised to use the column “hazard definition and hazard impact” of the ASAMPSA_E list of external hazards, to search the potential secondary hazards.

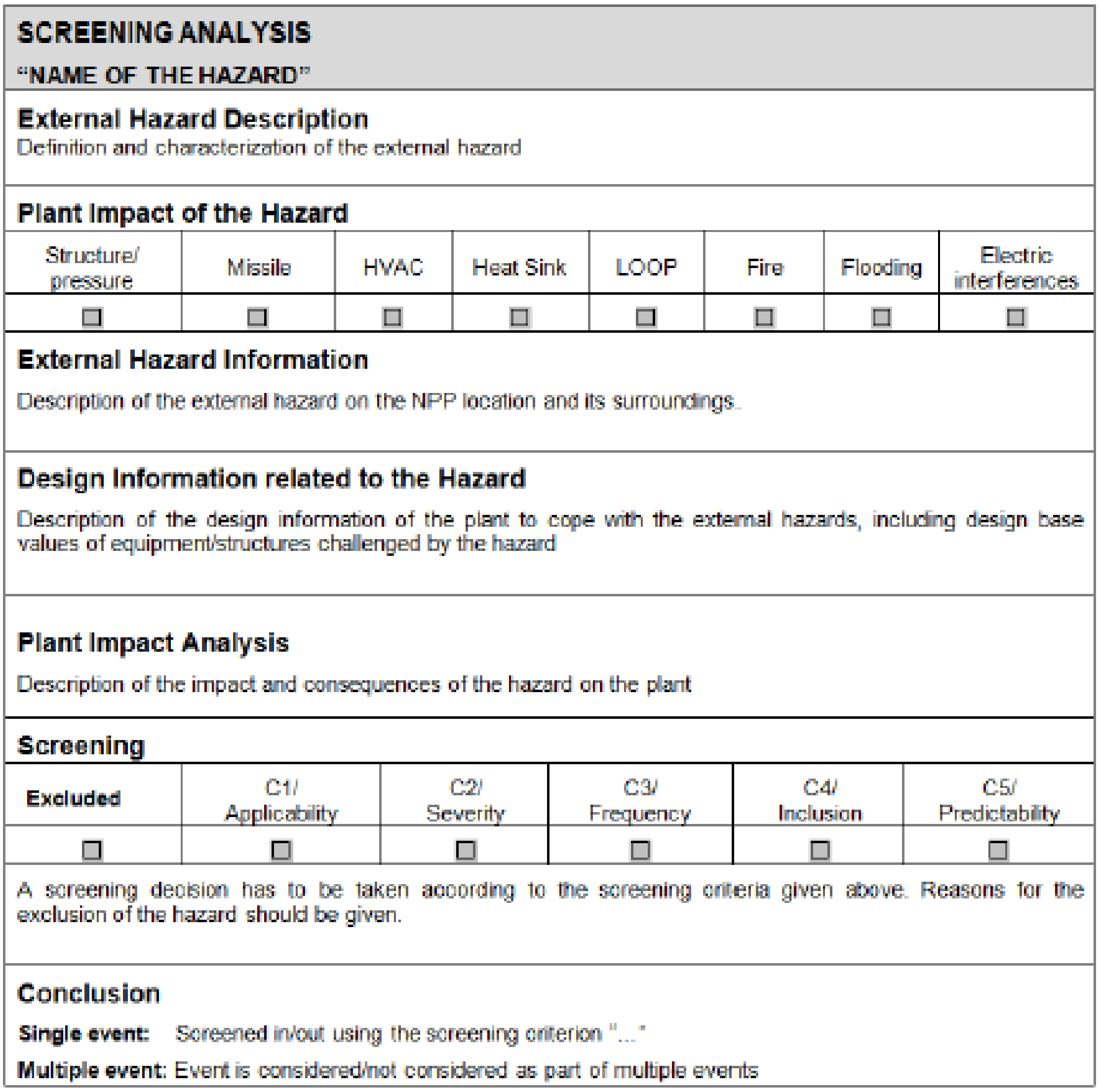
A screening analysis is then performed to identify among this list, the hazards that are relevant for the given NPP site and those that are insignificant or have insignificant effects.

Relevant external hazards for the PSA are those events which impact on the plant structures, systems or components with:

- The potential to degrade one or more plant safety functions and, at the same time,
- The potential to request the plant safety systems to keep the plant in a safe state or to

bring it in a safe state.

It is state of the practice to conduct and document the screening analysis of each external hazard, using a form, which includes a description of the event and its properties as well as an impact evaluation of the hazard on the plan site. An example of a standard form is given in Figure 4.



SCREENING ANALYSIS
“NAME OF THE HAZARD”

External Hazard Description
Definition and characterization of the external hazard

Plant Impact of the Hazard

Structure/ pressure	Missile	HVAC	Heat Sink	LOOP	Fire	Flooding	Electric interferences
☐	☐	☐	☐	☐	☐	☐	☐

External Hazard Information
Description of the external hazard on the NPP location and its surroundings.

Design Information related to the Hazard
Description of the design information of the plant to cope with the external hazards, including design base values of equipment/structures challenged by the hazard

Plant Impact Analysis
Description of the impact and consequences of the hazard on the plant

Screening

Excluded	C1/ Applicability	C2/ Severity	C3/ Frequency	C4/ Inclusion	C5/ Predictability
☐	☐	☐	☐	☐	☐

A screening decision has to be taken according to the screening criteria given above. Reasons for the exclusion of the hazard should be given.

Conclusion
Single event: Screened in/out using the screening criterion "..."
Multiple event: Event is considered/not considered as part of multiple events

Figure 4: Example of a standard form for the screening analysis of single external hazards

Five screening criteria detailed in Table 1 and adapted from ASAMPSA_E, D50, 19-2017, allow to disregard the hazard. However, this list of criteria is indicative as other criteria may be considered as soon as they clearly justify the reasons of exclusion of a hazard.

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Table 1: Screening criteria for a single external hazard

Criterion	Description
C1/ Applicability	The external hazard does not occur on the site or sufficiently close to the site and its relevant surroundings to have an impact.
C2/ Severity	The external hazard has a damage potential that is less or equal to another event, for which the plant is designed for.
C3/ Frequency	The hazard has an occurrence frequency at the site which is lower than an indicative target (*).
C4/ Inclusion	The external hazard is included in the definition of: - another external hazard analysed for the site; - the hazard leads to an initiating event already included in the level 1 PSA (with the same or very similar boundary conditions for the event tree modelling) and the frequency of the external hazard occurrence is negligible compared to the level 1 PSA frequency.
C5/ Predictability	The external hazard evolves sufficiently slow, so that there is a sufficient amount of time to eliminate the effects of the hazard or not to implement countermeasure actions.

(*) The target frequency of event to be considered is defined by the national authorities (ranging between 10^{-5} and 10^{-7} / year).

5.2.2 Hazard characterization methods

To characterize natural hazards, there are broadly two main approaches:

- Statistical approaches based on past phenomena to establish probabilities of occurrence for these same events in the future. In general, statistical extrapolation is required and it is often necessary to estimate levels beyond the range of observational data.
- Deterministic approaches that give a hazard level based on (generally) a worst-case scenario, without taking into account the probability of this event. Deterministic methods include naturalistic methods or the physical study of the phenomenon. In some cases, physical study of the phenomenon complements the statistical definition of the hazard.

Statistical methods enable quantitative evaluation of the hazard for a given occurrence, whereas naturalistic methods are primarily qualitative. Therefore, statistical methods are more appropriate for evaluating the hazard levels of natural risks, and are used in the present methodology.

These approaches relate a hazard level (intensity) to a given return period: either return period of a given intensity of the natural hazard or intensity level of the hazard for a given return period. This concept of return period assumes stationarity of the phenomenon being studied. This is often why it is easier to consider and use the annual exceedance of probability (AEP) instead of the return period.

The intensity of the hazard level is quantified by one or several key metrics. The choice of the key metric(s) to characterize a hazard depends on the metrics used in the existing datasets or historical data, and on the metrics used in the design of the NPP components

The relationship between the level intensity and the return period or the AEP, is shown on the hazard curve, which is the graphical representation of the hazard characterization.

When using statistical methods, the general approach for estimating the probability of extreme values is as follows:

- Collection on available data on the phenomenon to be studied. For most of the natural hazards, a lot of datasets or databases exists ;
- Sampling to establish a series of independent data characterising the tail of the distribution, the annual, maxima, any temporal period maxima or the independent cluster

maxima;
- Selection of the probability distribution to apply depending on the previous sampling. The GEV (Generalised Extreme Value) distribution is fitted to a series of annual maxima, and the GPD (Generalised Pareto Distribution) is fitted to the exceedance of cluster maxima above a high threshold;
- Fitting the statistical distribution to the sample. There are many methods available; the most common approaches are the method of moment, maximum likelihood method and Bayesian framework;
- Extrapolation of the fitted distribution to estimate extreme levels.

5.2.3 *Uncertainties of statistical methods*

It is necessary to carefully choose the data that are going to be analyzed when fitting an extreme value model to environmental model (IRSN, 2013). This method involves only keeping certain data considered to be relevant, either by only keeping the maxima over a defined period (Block Maxima approach), or by keeping only the values above a given threshold (peak Over Threshold approach), with this threshold determined by investigating how results change for a variety of different thresholds. Other methods can be used: for example Coles et al., 2001.

The uncertainty of the models also depends on the quantity and the period of available data. To compensate the lack of information, other measurements can be used, for example historical data resulting from indirect measurements (historical documents, sediments left by a historical flood, etc.) or analysis of observational data for a larger territory. In this case, it is necessary to check or assess the relevance of these other data.

It is possible to perform some validity tests to evaluate the accuracy of a model or the quality of data distribution. For example, a validity tests can be using a random part of the sample to construct the model, and using the other part to check the results obtained.

Lastly, for extreme return periods, the stationarity assumption can present great uncertainty, as past events are not necessarily representative of future events. In case it is not possible to assume the stationarity, the comparison of events occurring now and in the future is possible via conversion to AEP.

5.2.4 *Production of hazard curves (current practice and improved methods)*

5.2.4.1 *Earthquake*

There are two main methods of seismic hazard assessments: ones which are deterministic (DSHA) and that include a single scenario earthquake (historical, Maximum Credible Earthquake (MCE) or user-defined): or a probabilistic combination of earthquake scenarios in order to determine the hazard for a given area (PSHA).

A deterministic seismic hazard assessment (DSHA) consists of three main steps:

1) Define all possible sources to cause significant hazard at a site from historic, tectonic, geologic or geotechnical data.
2) Choose a fixed distance, fixed magnitude earthquake and place it on the closest position to the site on each source.
3) Estimate ground motions via GMPEs (ground motion prediction equations) at the site in terms of spectral ordinates. A common use is to consider ground motions which are one logarithmic standard deviation above the logarithmic mean (84th percentile motions). Each of these ground motions corresponding to each source is considered for design. A collection of GMPEs published by Douglas (2018) shows several hundred GMPEs for various tectonic regimes, countries and earthquake types all over the world.

DSHA is very useful for lifeline and critical facility locations and is increasingly being used to supplement a PSHA.

A probabilistic seismic hazard assessment (PSHA) considers all combinations for magnitude and distance to calculate the hazard, and consists of five main steps:

1) Define a probability of potential rupture locations for each source.
2) Determine the temporal distribution via recurrence relationships. The Gutenberg-Richter is commonly used.
3) GMPEs are used for the range of distances for each magnitude, to produce spectral ordinates dependent on the tectonic regime with aleatory variability.
4) The hazard must then be integrated by combining the effects of different size, location, source zone and occurrence probability earthquakes in order to calculate the expected number of exceedance of ground motions. From this, annual rate of occurrence are derived giving a hazard curve.
5) The PSHA results can next be disaggregated for a given variability, distance and magnitude triplet to perceive the hazard that contributes most for a given ground motion parameter.

There are a number of datasets covering Europe. Models have been developed by various entities over the last few decades taking into account the faults and uncertainties close to NPPs such that they are usable for the analysis. The SHARE model, as part of the Global Earthquake Model is the most common of these models, which can be used as part of site specific studies. Important at the site is the site effect data, however in many cases the detailed data is not available.

The causes of epistemic uncertainty in the earthquake hazard characterisation should be expertly weighted. The main factors are:

- the GMPEs;
- the maximum magnitude for every seismic source zone and the magnitude recurrence relationship;
- the earthquake catalogue completeness or stochastic nature and therefore the b-value within the Gutenberg-Richter relation;
- the recurrence interval of characteristic earthquakes (Poissonian / time-dependent);
- boundaries and determination of seismic zones.

Some innovative and improved analyses for earthquake hazard characterisation are presented in NARSIS deliverable D1.5. A key focus is made on:

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

The purpose of these improved methods is to define a design ground motion in terms of return periods, which takes the primary and secondary effects (aftershocks, tsunami) into account.

Furthermore, the application of CMS (conditional mean spectra) and the potential use as part of the characterisation of the spectra is described in D1.5. The use of a CMS is important in terms of the potential scaling factors of the spectra.

5.2.4.2 Tsunami and wave

Tsunamis can be generally analysed deterministically (DTHA: Deterministic Tsunami Hazard assessment) with simulation of wave propagation.

Probabilistic tsunami hazard assessments (PTHAs) are also possible but do not have a common methodological framework. The final product is the exceedance curve of expected maximum wave heights at a specific site with respect to return period.

The NEAM tsunami hazard model 2018 (NEAMTHM18) is a probabilistic hazard model for tsunamis generated by earthquakes. It covers the coastlines of the North-East Atlantic, the Mediterranean and connected seas (NEAM). The hazard results are provided by hazard curves calculated at 2343 points of interest.

DTHA appears as the most conservative approach and is used in most of the forecasting tools in operational context. PTHA has the advantage to better target the most affected regions and to determine the most dangerous sources for a chosen region and return period. PTHA aggregates numerous scenarios in order to take into account various sources of tsunamis (location and intensity).

In DTHA, the quantification of tsunami hazard is generally prone to large uncertainties. First of all, the triggering event occurs with a significant uncertainty in regards of its very long return period which is beyond the so-far recorded history. Further on, wave propagation models have been developed especially for the application in deep water environments. Those models cannot accurately capture onshore processes. Finally, the underlying data to tsunami waves simulation, as the bathymetric models, are not everywhere of sufficiently high quality. Resolutions much higher than 100 m are recommended and bathymetric data on such a scale is often not available or difficult to acquire.

The whole process to compute the PTHA also includes many uncertainties, which have to be integrated into the approach. In particular, the list of earthquakes to calculate the distribution law and the list of unity faults of the fault system to create the rupture catalogue are not exhaustive. The uncertain distribution of fault slip, especially in the near field context, can also have a significant impact on the nearshore wave propagation. This needs to be taken into account.

Due to all those limitations, tsunami hazard models demand a high-level expert judgement. Some advanced methodologies for PTHA workflow, with application on Mediterranean Sea and scenario stochastic generation for tsunami, are described and tested in NARSIS deliverable D1.2.

5.2.4.3 Extreme weather

Extreme weather includes a number of key perils identified in the ASAMPSA_E list of natural hazards.

For NPP specific assessment, most of the methods of extreme weather hazard characterisation involve some form of extreme value (EVM: extreme value model). The most common ones involve annual maxima or the PoT (Peak over Threshold) methods.

There exist number of datasets for station data across Europe. Station data is required to develop the extreme value statistics to produce the hazard curves.

Where data are incomplete, there are issues to complete the data. Asymptotic estimators and/ or expectation-maximization algorithms can be used, but give no clear increase. Thus, data collection is crucial to the stochastic modelling and simulations, and examination of whether neighbouring site data can be applied, as well as the complements via historical data, is required. Estimation of uncertainties along the whole data chain is required. To do so, physical or statistical models can be used.

In general, one can consider the following possibilities of using data from numerical simulations:

- Meteorological data from numerical weather forecasts made in the past. Most national weather services have sets of prognostics data from simulations performed over many years. These data can be useful for reanalysis.
- The aforementioned data can be applied in ensemble systems, allowing the estimation of probabilities of occurrence of rare meteorological phenomena under consideration. This takes account of extreme conditions that could have happened in the past with some probability. Additionally, the data are available on grids that are much denser than the monitoring meteorological network.

- Data from reanalysis can also be applied for performing climatic modelling by providing projection of weather conditions for the future NPPs.
- Simulations can also be performed for facilities other than NPPs and then geo-statistical methods can be applied to provide an estimate for NPP.

5.2.4.4 Flooding

Flooding risk can be associated with various phenomena, in particular:

- Lowland flooding associated with a slow overflowing of a river that floods its flood plain over a long time;
- Torrential floods associated with heavy precipitation over a limited catchment;
- Rising groundwater, mainly observed in plains in low or poorly drained lands, when alluvial groundwater comes to the surface;
- Precipitation run-off associated with extreme precipitation. This phenomenon is accentuated by land artificialisation;
- Discharges from networks, which can lead to delocalised flooding, by overloading the underground networks, especially drainage systems.

Basic nuclear installation (and pressurized water reactors) is calculated based on the flow of the 1000 year flood considering the upper bound of the 70% confidence interval increased by 15% (ASN guide n°13, 2013), i.e. a return period longer than the thousand-year flood.

The different flooding hazards characterisation are based on modelling tools to assess the risks in a given place, for a given occurrence. These tools shall take into account local characteristics that can influence the hazards, such as the topography of the terrain, land use, existing drainage structures, protection systems, etc. To construct a hydraulic model, the terrain model must be sufficient to include the whole flood plain for extreme flood, but also large enough upstream and downstream of the site being studied to obtain a stationary model with regards to the limit conditions.

The hydro-geomorphological approach is a complementary approach used to determine, based on the study of sediments and the topography of the terrain, the possible flood plain.

The evaluation of hazards, in particular for low frequencies, rely often on statistical methods based on observation of past events, which has inherent uncertainties. Historical data are given in one or more nearby measuring stations. Depending on the site studied, one or more stations may be necessary. In this case, care should be taken to compare the of results between nearby station, the use of station upstream a confluence, the representativeness of the catchment area, etc.

It should be noted that when studying extreme floods, bias of the measurements associated with the flow control structures (dams, tanks, etc.) should be considered. To obtain reliable data for extreme events, conservative flow rates should be considered with pessimistic assumptions associated with flood suppression structures.

Regarding uncertainties, the first source of uncertainty in the evaluation of flooding hazard is the quality of the available data. Besides, the assumed stationarity of the sample may present some bias with significant consequences for the evaluation of extreme events. For extreme precipitation data, the uncertainty is mainly driven by the length of the sample available for the estimation of the return level of interest.

Uncertainty is also caused by the fact that data from local measuring stations needs to be used for extrapolation as there are generally no data available at the site itself.

These uncertainties can be evaluated through a sensitivity study, in particular for the most influential variables. For example, the propagation of uncertainties in hydraulic modelling is possible using a Monte Carlo type method (Fahsi, 2011), (Nguyen, 2013).

Furthermore, the uncertainty associated with climate change must be also considered.

In general, evaluation of flood risk comes under an assessment performed by specialist engineers with the appropriate knowledge, thus limiting the uncertainty related to the choice of models or the probabilistic laws employed.

Some advanced methods are also presented in NARSIS deliverable D1.3, in particular in order to address combination of phenomena involving flooding events. To develop a better understanding of how a set of different hazards can combine to result in a major flooding event, multivariate extreme value models are required. Uncertainties associated to those methods are defined and studied in D1.3.

5.2.5 Thresholds of damage (capacity) of NPP components

The occurrence of external hazard affects the different NPP components but each component has a different vulnerability to the effects caused by the hazard. Conceptually, a threshold of a given intensity measure of the hazard (i.e. ground motion acceleration or response spectra for earthquake, run-up height for tsunami, water level for flooding) applies to each component and each single hazard. The vulnerability of a NPP component is thus site specific and hazard specific. For practical reasons the explicit evaluation of the individual threshold value is always limited to a subset of components, following some procedures that have been introduced and optimized over the last decades, such as walkdown-based screening with respect to seismic events.

The NARSIS MHE (Multi-Hazard Explorer) open source software proposes an indicative list of SSC (systems, structures, components), for which the thresholds can be defined:

- Auxiliary cooling system
- Battery
- Offsite power
- Emergency diesel generator
- Road network
- Turbine driven auxiliary feed water
- Letdown isolation system.

The SSC (systems, structures, components) forming this list can be classified depending on whether they fulfil a safety function or whether they fulfil only an operational function.

Examples of the former class are batteries, emergency diesel generators and turbine driven auxiliary feed water. SSC of the latter class are, for example, offsite power and road networks.

Of course, additional critical components can be considered for each NPP site.

It is worth to notice that the vulnerability of a NPP component is not a totally intrinsic property and may vary in the time. For instance, the hazards may lead to a higher damageability due to time-variant parameters such as aging, corrosion or human actions. Furthermore, a cluster of hazards with simultaneous occurrence may also affect the damage of components with the hazard interactions changing the component vulnerability that could lead to reduce the threshold value.

5.3 Level 1: multi-hazard assessment scoping through potential site hazard

Level 1 enters into the multi-hazard assessment through a qualitative analysis, having the following purposes:

- The identification of possible correlations between single hazards identified at Level 0;
- The introduction of the time factor by considering an analysis time window and by taking into account the dynamic vulnerability of the NPP components that depend on the effects caused by the initiating event.

At this stage, in addition to the event duration assessed at Level 0, it is thus necessary to define:

- The analysis time window: this is the time window desired for the hazard assessment, which is typically one year but is generally site specific;
- The operational time window: the duration taken for the hazard effect to subside and the associated plant checks, damage repairs and safety procedures to occur.

Level 1 analysis uses a qualitative list of questions to decide whether a multi-hazard approach is necessary for the particular site: a set of questions (not exhaustive) is provided in Table 2.

The answer to these questions may be a challenging task that has to be submitted to expert judgement. If at least one of the Yes/No questions obtains a Yes, the framework process goes on and multi-hazards scenarios shall be identified and assessed, the end-user moves on to Level 2 to make a first-pass assessment of the effects of dynamic hazard and time-dependant vulnerability. Otherwise, the process stops.

Table 2: Level 1 qualitative list of questions to initiate the multi-hazard assessment process

	Question	Comment
Contextual questions	What is the purpose of the risk assessment exercise?	Optimal risk mitigation, PSA, most critical risk scenarios, adequacy of resources, level of preparedness for post-event response
	Which natural hazards are relevant?	For each NPP component: list of natural hazards remaining after Level 0 analysis
	What is the analysis time window?	Time window desired for the hazard assessment, which is often determined in annual probability but is generally site specific.
	What is the operational time window of each NPP component, in case of significant loss?	Duration taken for the hazard effect to subside and the associated plant checks, damage repairs and safety procedures to occur. The operational time window is very plant and component specific.
Yes / No questions	If only one hazard is identified, is the probability that this could happen more than once in the time window with significant loss, higher than an indicative target?	Depends on probability of occurrence of the single hazard compared to the analysis time window: yes or no
	If more than one hazard is identified, could a hazard trigger another hazard in the list?	Cascading event: yes or no.
	If more than one hazard, could hazards occur “simultaneously” or in the same time window and are caused by the same external factors?	Compound or associated hazards i.e. earthquake and volcanic eruption from the same tectonic process: yes or no.
	If more than one hazard, could hazards occur “simultaneously” or in the same time window, but not caused by the same external factors?	Conjoint independent events i.e. hurricane and earthquake occurring “simultaneously”: yes or no
	If more than one hazard, could the occurrence of one of the hazards influence the vulnerability of elements to another event?	Dynamic vulnerability i.e. a building primarily damaged by an earthquake, then having higher vulnerability to floods or storm due to cracking: yes or no.
	If more than one hazard, could one of the hazards significantly influence the occurrence probability of other hazards?	Dynamic hazard i.e. a large earthquake weakening soil and increasing probability of landslides during extreme precipitation: yes or no.
	Additional questions	A number of NPP specific questions with reference to the regulatory need for multi-hazard analysis should be added here.

5.4 Level 2: multi-hazard interaction matrix

5.4.1 Identification of interaction types

Level 2 is then implemented in order to:

- Identify the multi-hazards scenarios i.e., the hazard combinations with the time ordering of the events (causes and effects) and account for the dynamic vulnerability;
- To attribute a score of the "credibility" of each multi-hazard scenario. This score can be used to prioritize the quantitative assessment.

The first step of Level 2 is to check the type of interaction, between hazard pairings, through a correlation matrix in which each single external hazard found relevant on the NPP site is systematically combined with another one. An indicator depending on the type of interactions found, is assigned to this combination. Six indicators are defined:

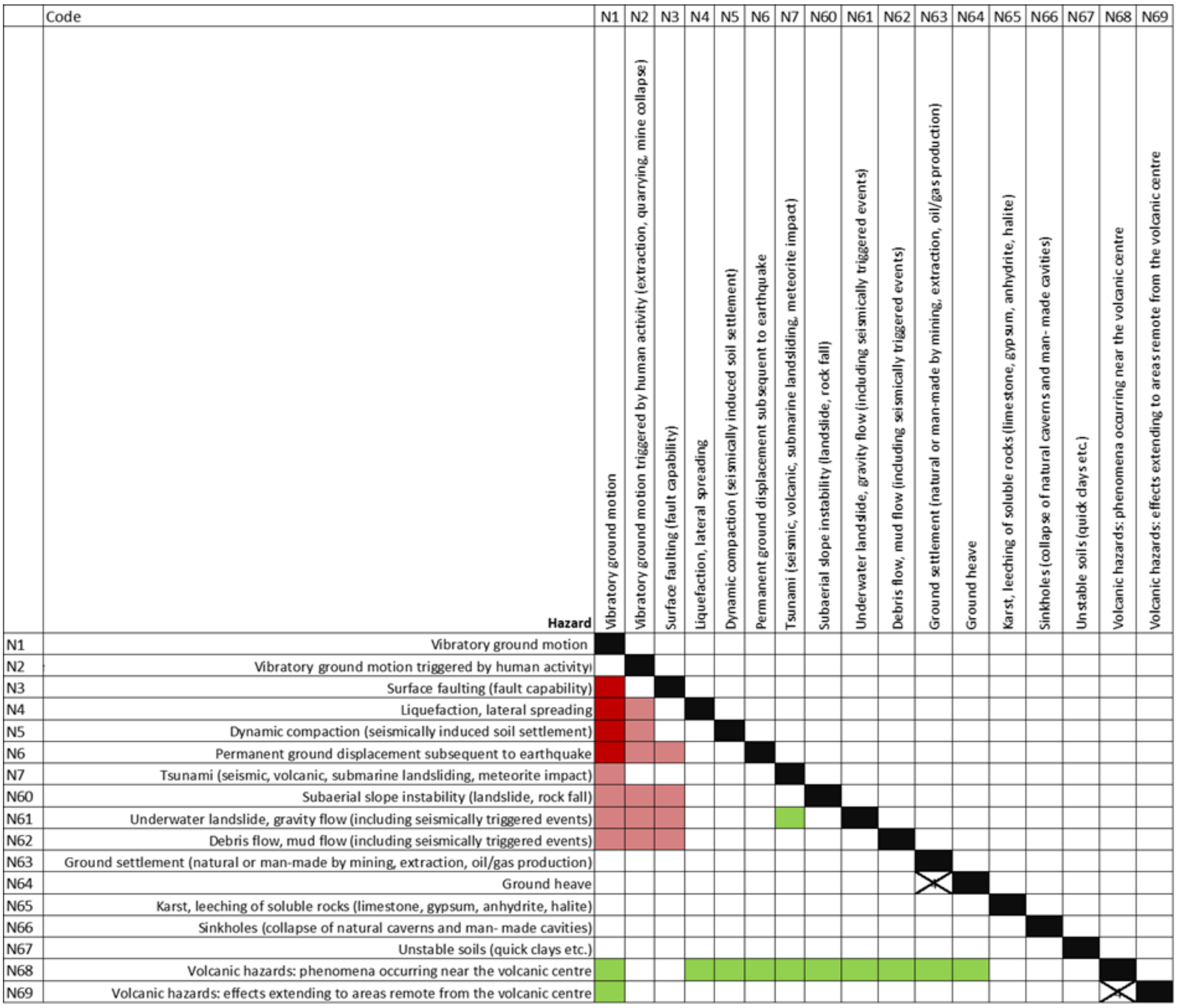
- Hazard 2 is a prerequisite for hazard 1
- Hazard 2 may cause hazard 1
- Hazards 1 and 2 are associated (common root cause)
- Hazard 1 may cause hazard 2
- Hazard 1 is a prerequisite for hazard 2
- Hazards 1 and 2 are mutually exclusive.

The cells without indicators correspond to independent hazards.

An example is shown on Figure 5.

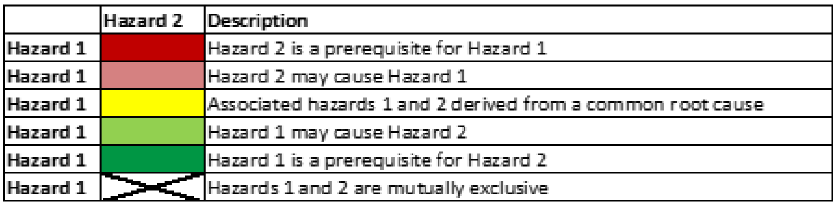
The full Excel files and methodology is summarised below for a few of the interactions. It should be noted that these are only 2 dimensional interactions, and additional hazard combinations should also be examined as needed via expert judgment.

If there is more than one hazard relevant to the NPP, but no interaction is found between them, then the hazards are independent. In this case, the end-user directly moves on to Level 4 (quantitative analysis of multi-hazard scenarios) using the NARSIS MHE open software (see section 5.6.3).



	Code	N1	N2	N3	N4	N5	N6	N7	N60	N61	N62	N63	N64	N65	N66	N67	N68	N69
	Hazard	Vibratory ground motion	Vibratory ground motion triggered by human activity (extraction, quarrying, mine collapse)	Surface faulting (fault capability)	Liquefaction, lateral spreading	Dynamic compaction (seismically induced soil settlement)	Permanent ground displacement subsequent to earthquake	Tsunami (seismic, volcanic, submarine landsliding, meteorite impact)	Subaerial slope instability (landslide, rock fall)	Underwater landslide, gravity flow (including seismically triggered events)	Debris flow, mud flow (including seismically triggered events)	Ground settlement (natural or man-made by mining, extraction, oil/gas production)	Ground heave	Karst, leeching of soluble rocks (limestone, gypsum, anhydrite, halite)	Sinkholes (collapse of natural caverns and man- made cavities)	Unstable soils (quick clays etc.)	Volcanic hazards: phenomena occurring near the volcanic centre	Volcanic hazards: effects extending to areas remote from the volcanic centre
N1	Vibratory ground motion	■																
N2	Vibratory ground motion triggered by human activity		■															
N3	Surface faulting (fault capability)	🟥		■														
N4	Liquefaction, lateral spreading	🟥	▧		■													
N5	Dynamic compaction (seismically induced soil settlement)	🟥	▧			■												
N6	Permanent ground displacement subsequent to earthquake	🟥	▧	▧			■											
N7	Tsunami (seismic, volcanic, submarine landsliding, meteorite impact)	▧						■										
N60	Subaerial slope instability (landslide, rock fall)	▧	▧	▧					■									
N61	Underwater landslide, gravity flow (including seismically triggered events)	▧	▧	▧				🟩		■								
N62	Debris flow, mud flow (including seismically triggered events)	▧	▧	▧							■							
N63	Ground settlement (natural or man-made by mining, extraction, oil/gas production)											■						
N64	Ground heave											☒	■					
N65	Karst, leeching of soluble rocks (limestone, gypsum, anhydrite, halite)													■				
N66	Sinkholes (collapse of natural caverns and man- made cavities)														■			
N67	Unstable soils (quick clays etc.)															■		
N68	Volcanic hazards: phenomena occurring near the volcanic centre	🟩			🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩				■	
N69	Volcanic hazards: effects extending to areas remote from the volcanic centre	🟩															☒	■

Figure 5: Example of Level 2 correlation matrix



	Hazard 2	Description
Hazard 1	🟥	Hazard 2 is a prerequisite for Hazard 1
Hazard 1	▧	Hazard 2 may cause Hazard 1
Hazard 1	🟨	Associated hazards 1 and 2 derived from a common root cause
Hazard 1	🟩	Hazard 1 may cause Hazard 2
Hazard 1	▩	Hazard 1 is a prerequisite for Hazard 2
Hazard 1	☒	Hazards 1 and 2 are mutually exclusive

Figure 6: Legend of indicators

5.4.2 Hazard interaction Index

The second step of Level 2 consists in scoring the intensity of interactions between pairs of hazards, for all the possible pairs. All the single hazards are placed in a diagonal of a new matrix, as indicated on Figure 7 below. The matrix system provides rows and columns in terms of causes and effects. For each possible pair of hazards H_i and H_j, materialized by a cell in the grid, the user:

- Describes in a few words how the hazard Hi physically interacts with Hj (see Figure 7 b and c), taking into account the order between them (How does hazard Hi influence Hj? and vice-versa);
- Provides a score value ranging from 0 (no interaction) to (3 strong interaction) as a function of the interaction intensity (see Figure 7 d and e).

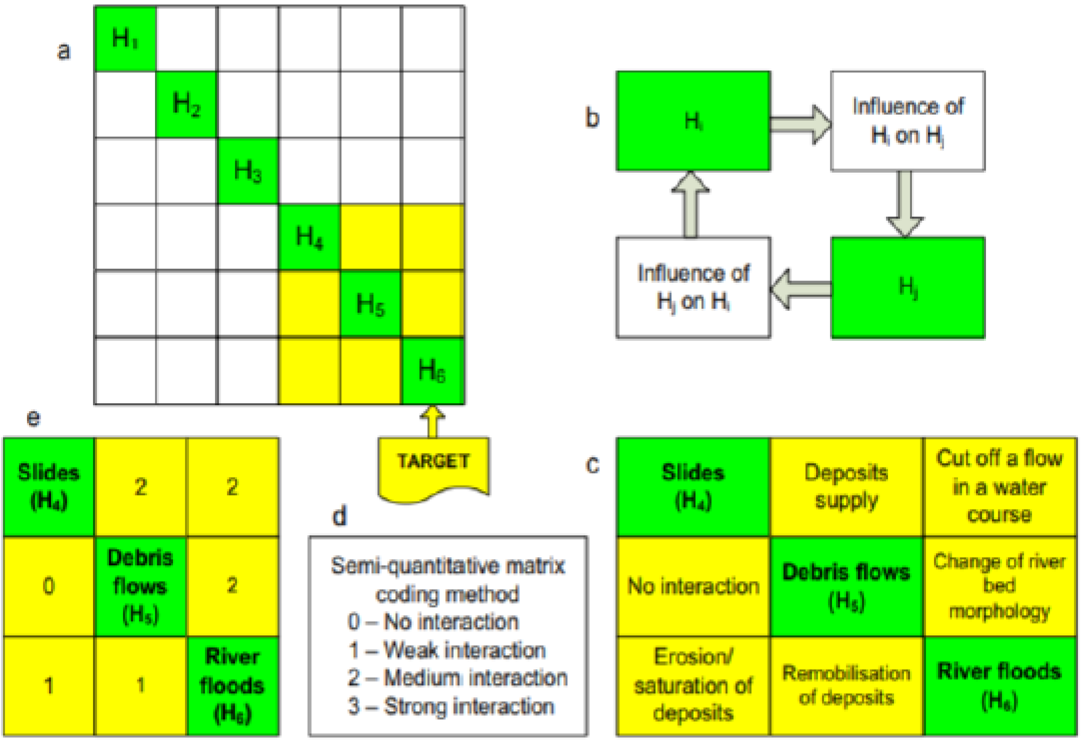


Figure 7: Causes and effects interaction matrix

Once all the hazards in the matrix are filled, it is possible to verify the degree of the impact of each hazard on the others, and the effect from other hazards by giving a global score to each hazard by summing the values obtained for causes (rows) and effects (columns), see Table 3, for the previous example.

Table 3: Calculation of the hazard interaction index (HI)

Hazard number	Hazard	Causes (rows)	Effects (columns)	Causes & Effects	Max possible score
H4	Slides	4	1	5	12
H5	Debris flows	2	3	5	12
H6	River floods	2	4	6	12
Total		8	8	16	36

In the proposed example, the “river floods” hazards get the highest (causes + effects) score, it is the hazard that plays the major role in the examined combinations.

The comparison of the (causes + effects) value to the maximum possible score shows the degree of credibility that the given hazard may be involved in cascade events.

In order to avoid the excessive weighting of a single hazard, the hazard interaction index HI, which is the sum of the codes for all the off-diagonal terms, is evaluated and compared to a threshold value.

The maximal possible value for the total sum of causes and effects is: $HI_{max} = 6 \cdot n \cdot (n-1)$, where n is the number of hazards.

Given the uncertainties and possible excessive or moderate weighting of single hazards, a threshold interaction index $HI_{threshold}$ equal to 50% of HI_{max} is recommended for considering a Level 4 quantitative analysis. If the hazard interaction index is less than this threshold, the quantitative analysis is not recommended because the additional accuracy gained by the detailed analysis is most likely within the uncertainty bounds of the simplified multi-risk estimates (Liu and al. 2014).

In the current example, $HI = 16$, $HI_{max} = 36$, $HI_{threshold} = 18$, $HI < HI_{threshold}$, the quantitative analysis is not recommended.

5.5 Level 3: modellability matrix

Before starting the quantitative calculations of the multi-hazards scenarios (Level 4), Level 3 is necessary to decide what can be modelled at the site for the different hazards combinations. In terms of the modelling matrix, the standards from WENRA and IAEA should be consulted, as well as the hazard and risk specialists that are able to quantify such a matrix.

The purpose of the modellability matrix is to ensure that the Level 4 analysis is feasible, in the sense that the interactions are amenable to mathematical modeling. Different factors may have an impact on the modellability of natural hazards and calculation of their effects:

- The quality and quantity of input data;
- The weight of the main hypotheses on the results, and the number of parameters that may influence the results;
- The chosen method;
- The physical complexity of the events.

As part of the choice of the methods, the use of different methods such as empirical, stochastic and mechanical models should be evaluated in order to see that different model results can be examined via more than one methodology or that a singular methodology is the best available for that particular dataset and site (Figure 8).

Expert Elicitation is an important part of this component, where all hazard combinations would need to be evaluated as to their qualitative and quantitative applicability.

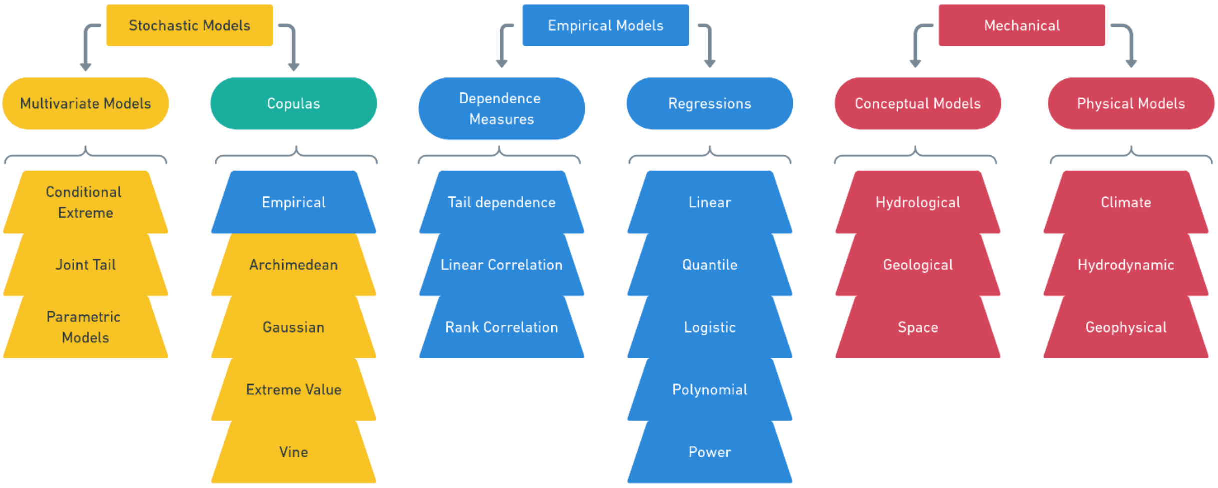
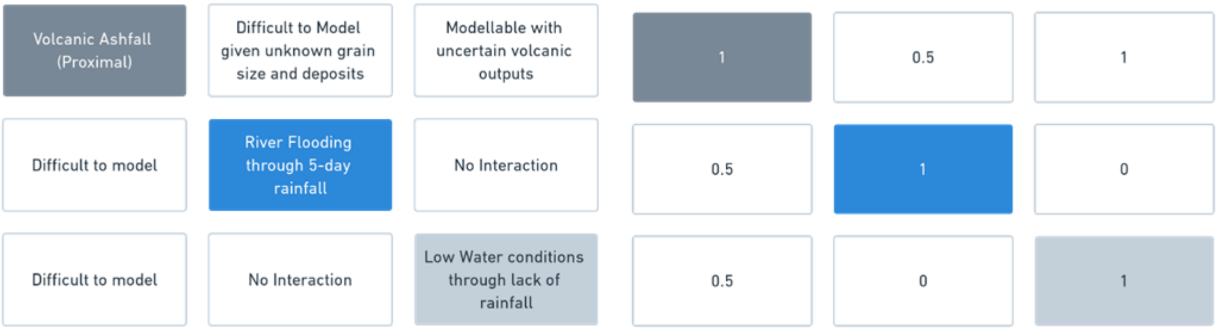


Figure 8: Types of stochastic, empirical and mechanical methods for analysing single and multiple hazard combinations (adapted from Tilloy et al., 2019)

Once the method chosen, the modellability matrix is applied (Figure 9). A value to quantify the possibility and reliability of event modelling is provided by the expert for a particular pairing of hazards:

- 0: not possible to model or no interaction
- 0.5: difficult to model or
- 1: modellable



Volcanic Ashfall (Proximal)	Difficult to Model given unknown grain size and deposits	Modellable with uncertain volcanic outputs	1	0.5	1
Difficult to model	River Flooding through 5-day rainfall	No Interaction	0.5	1	0
Difficult to model	No Interaction	Low Water conditions through lack of rainfall	0.5	0	1

Figure 9: Example of modellability matrix

The decision to perform the quantitative analysis (Level 4) is based on this matrix. When the value is 1, the quantitative analysis can be undertaken. For a value of 0.5, it can be necessary to perform specific studies to improve the quality or quantity of input data. If there is a triplet of hazards, values in terms of the possible modelling of the interactions need to be checked for the holistic case in addition with all interactions examined rather than a single pairing.

5.6 Level 4: quantitative analysis of multiple hazard probabilities

If Level 3 shows the possibility to undertake detailed quantitative analysis of the critical combination of independent or dependent hazards, Level 4 quantitative analysis is undertaken to calculate the combined probability of exceedance.

5.6.1 Assessing the probability of multi-hazard scenarios

The assessment of the probability of combined hazards depends on the type of interaction between them. If there is no time-variant vulnerability, the calculation of the combined probability is performed as indicated in Table 4.

When a time-dependent vulnerability of the NPP component has to be taken into account in the multi-hazard scenario, a multi-risk assessment model based on Bayesian Networks (BN) is introduced (Marzocchi et al. 2012, Liu et al. 2015), to both estimate the triggering / cascade effect and to model the time dependent vulnerability of a system exposed to multi-hazard (see Figure 10). BN make it possible to handle uncertainties yet still provide a flexible enough structure to analyse these cascade and conjoint events.

Table 4: Types of external hazards correlations categories

Type of correlated hazards	**Description**	**Calculation of the hazard combination probability** $P(A \cap B)$
Mutually exclusive hazards	The occurrence of one hazard excludes the occurrence of the 2nd one (e.g., high sea water level and low sea water level)	$P(A \cap B) = 0$
Coincidental (non-correlated) hazards; or non-causally correlated hazards	The hazards occur simultaneously without a common mechanism. The hazards are independent (e.g., air plane crash and low sea water level)	$P(A \cap B) = P(A) * P(B)$ with: $P(A)$: probability of the occurrence of A $P(B)$: probability of the occurrence of B
Causally correlated hazards	*Linked by a cause-effect relation (consequential)*: The occurrence of the 1st hazard induces the 2nd hazard, i.e. the 1st one is a pre-requisite for a correlated hazard (e.g., heavy rain and landslides)	$P(A \cap B) = P(B/A) * P(A)$ with: $P(B/A)$: conditional probability of the occurrence of B given the occurrence of A $P(A)$: probability of the occurrence of A
	Linked by a common-root cause: The hazards occur simultaneously due to a common root cause (e.g., meteorological situation). The hazards are generally not correlated between them but to the root cause.	$P(A \cap B) = f *$ $P(ROOT\ CAUSE)$ with: f as a correlation factor between the root cause and the hazards occurrence $P(ROOT\ CAUSE)$: probability of occurrence of the root cause

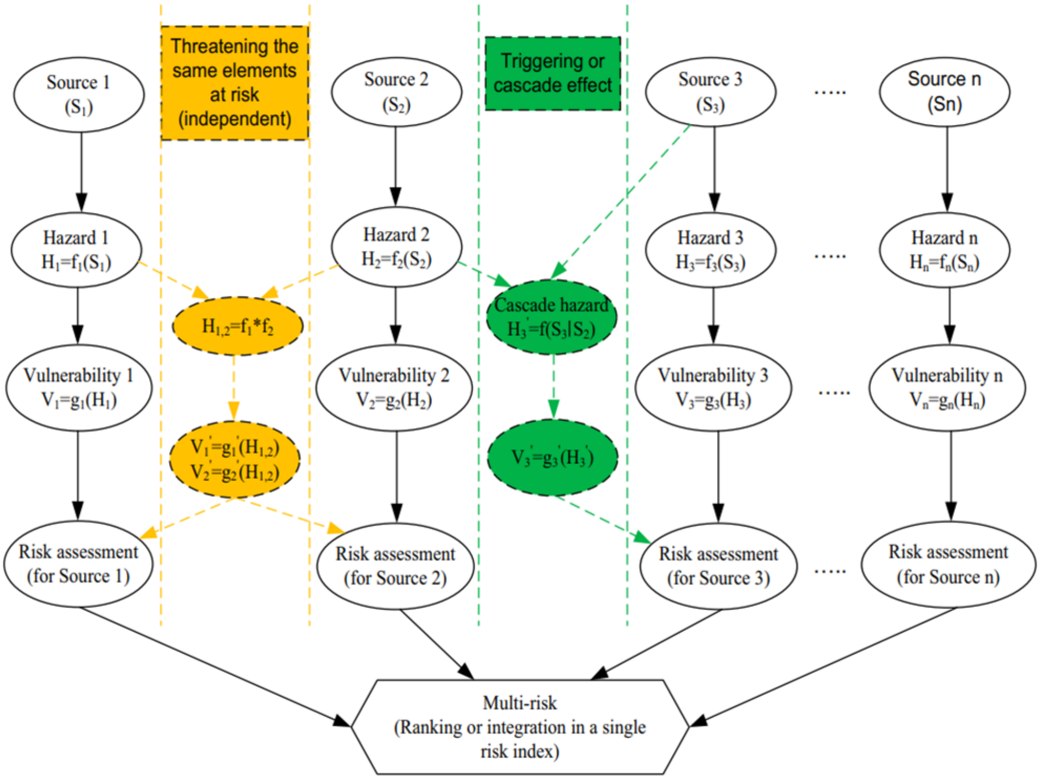


Figure 10: BN-based quantitative multi-risk assessment for time-dependent vulnerability

5.6.2 Modelling the effects of multi-hazard scenarios

To get a reliable response of the NPP components, the physical modelling of the hazard interactions needs to be temporally consistent (i.e. respecting the time ordering of the events).

As part of the analysis, here are examples of tools that can be used and/or which are openly available to model hazard results for a NPP site for various hazards:

- Mechanical: BASEMENT, Delft3D, Next Generation Hydro Suite, PLAXIS2D, Titan2D
- Empirical: MvHAST, LAHARZ
- Stochastic: CLIMADA, OpenQuake

Uncertainty quantification can be undertaken using a range of methodologies, from global to local analysis, with examples detailed within NARSIS deliverables D1.2-D1.5. In addition, Chapter 7.2 of D1.3 dealt with the uncertainties associated with univariate and multivariate extreme value analysis.

The difficulty of uncertainty analysis depends on the type of method used and the complexity of a dependent multiple hazard interaction. A number of packages for uncertainty analysis exist as detailed within D2.3; their capabilities include the evaluation of Sensitivity Indices, Global Sensitivity Analysis (GSA), and other uncertainty methods.

5.6.3 Case of combinations of independent hazards (NARSIS-MHE Open software)

To perform a multi-hazard assessment of independent hazards, the open source software tool NARSIS Multi-hazard Explorer (MHE) is recommended (https://github.com/a-schaefer/NARSIS-MHE/releases/tag/v1.0).

It covers the assessment of different generic sites, hazard curves, vulnerability thresholds and hazard combinations. In addition, it allows for simple visualization of results.

The software needs two kinds of inputs. First, it needs multiple hazard curves, which should be independent from each other in the first instance. Such a hazard curve provides the occurrence probability or return period of one or more hazard intensity metrics. Each of these curves needs to be computed independently.

Secondly, SSC (Systems, Structures and components) and associated thresholds have to be defined. For each SSC exceedance thresholds are assigned for the individual hazards, specifying the level at which a critical vulnerability state is reached. These thresholds are used to identify dominating hazards which have the highest probability to exceed a critical vulnerability. By default, 7 components are already provided by the software.

From these input data, multi-hazard curves for different return periods are computed, by providing the relationship between 2 hazards with respect to a certain return periods like 10,000 years (adjustable via input). Only two hazards can be directly compared at once, however, multiple iterations could be made where the output for two hazards is used as input for a third hazard. Since only one hazard is considered as primary or dominant it is then compared to all other available hazards. A multi-hazard combination relies on a so-called look-ahead-time or “hazard time window” which describes the time window after the occurrence of the primary hazard in which a second hazard event may happen.

6 Conclusions and recommendations

This deliverable presents and describes the multi-hazard assessment framework developed in Work Package 1 of NARSIS project. The proposed methodology is based on the MATRIX approach, from Liu and al. (2015), with complements and adaptations for the NPP specific nature. The framework includes five successive levels:

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

The approach developed here makes the multi-hazard assessment possible at the scale of a nuclear power plant. It should however be noticed that the multi-hazard approach is very plant specific, and although the methodology should screen all hazard types along the lines of the modified single hazards explored within ASAMPSA_E, and all the scenarios, there are still some combinations, which may be missed due to specific vulnerability loops, and/or dynamic hazard loops. In this way, the multi-hazard framework needs further calibration with WP2, WP3 and WP4, and is susceptible to be updated at completion of these work packages.

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

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

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

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

The step from single to multi-hazard analysis involves the identification of secondary hazards and the consideration of possible interrelation between single hazards either in terms of spatial or temporal interactions. The integrated framework enables to check all the possible combinations of single hazards, to qualify different types of interactions and to assess quantitatively (via the hazard interaction index), the credibility and intensity of these interactions. It is thus possible to decide which multi-hazard scenarios are the most realistic. The last steps of the integrated framework enable to assess the modellability of the multi-hazard scenario and proceed to the numerical calculations of the probability occurrence of the given scenario and of these effects on the NPP components.

In the case of independent single natural hazards, the open source software tool NARSIS Multi-hazard Explorer (MHE) is recommended or further adjustments to the software.

Uncertainty forms a major part of any result, given the large variability of events, the quantity and reliability of datasets (epistemic uncertainty) and simply the random nature of natural hazards (aleatory variability). Uncertainty quantification has to be taken into account at each step of the framework, from the hazard source to the site effects. Uncertainty quantification is particularly relevant whenever historical data are extrapolated in order to derive statements about return periods that are far longer than historical records.

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

In addition to the approach developed in this document, it is recommended to initiate a so-called pilot study (i.e. a multi-hazard analysis for an operating NPP) to help to establish the proposed framework by demonstrating that it is feasible for the industry.

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Annex A: Suggesting list of secondary hazards

Initiating event	Type of effect	Name
Earthquakes	Primary effects	Ground shaking
		Fault and ground rupture
	Secondary effects	Tsunami
		Landslide, slope failure
		Liquefaction, lateral spreading
		Settlement
		Fire
		Dam breaks, flooding
	Tertiary effects	Epidemics
		Socio-psychological
		Economical
		Environmental
Volcanic activity	Primary effects	Ash fall, tephra
		Ground shaking
		Lava flows
		Lahars
		Release of gas
		Ground deformation
		Fire
		…
	Secondary effects	Flooding or low water level due to obstruction of a river
		Epidemics
		…
Extreme precipitation	Primary effects	Flash flood
		Bore
		Humidity, extreme atmospheric moisture
		Landslides, slope failure
		Snow avalanche
		High groundwater level
		Debris flow, mud flow
	Secondary effects	Floods resulting from changes in water channel, sedimentation or erosion
		Flood, dam break due to landslides
		…
Extreme drought	Primary effects	Low groundwater level
		Fire
	Secondary effects	Ground settlement
		…
Hurricane, tropical cyclone	Primary effects	High wind
		Tornado
		Lightning
		Seawater level, storm surge
		Hail
	Secondary effects	Flooding
		Landslides, slope failure
		Debris flow, mud flow
		…