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PROBABILISTIC SAFETY ASSESSMENT OF NPPS AGAINST COMBINED NATURAL HAZARDS: OUTCOMES OF THE NARSIS PROJECT

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ABSTRACT

The H2020-NARSIS project was launched in order to investigate the possible improvements to be integrated in extended Probabilistic Safety Assessment (PSA) procedures for Nuclear Power Plants (NPP) related to single, cascade and combined external natural hazards. It has coordinated the research efforts of 18 partners encompassing leading universities, research institutes, technical support organizations, nuclear power producers and suppliers, reactor designers and operators from 10 countries in Europe. As part of the effort of the consortium, many datasets have been collected, states of the art produced and methodologies tested, which have led to the development and release of various software tools. Some guidelines and recommendations for use in nuclear safety assessment have been prepared as well. In this paper, we give an overview of the main challenges addressed by NARSIS, together with the main achievements.

MAIN CHALLENGES ADDRESSED BY NARSIS

The Probabilistic Safety Assessment (PSA) procedure allows practitioners to better understand the most causes prone to initiate nuclear accidents and to identify the most critical elements of the systems. However, despite the remarkable reliability of the PSA methodology, lessons learnt from the Fukushima Daiichi nuclear disaster pointed out the necessity of upgrading the current methodological framework related to areas such as cascading and/or conjunct events characterization, structural and equipment responses and uncertainties treatment. New developments in those areas would even enable the extension of their use in accident management.

Based on these lessons, as well as on the FP7-ASAMPSA_E project results and on the outcomes from other European FP7 projects (e.g. SYNER-G, MATRIX, INFRARISK), the NARSIS project ("New Approach to Reactor Safety ImprovementS", 2017-2022) aimed at proposing progress in PSA Fundamentals for Nuclear Power Plant (NPP) Safety, in relation with single, cascade and combined external natural hazards (e.g., earthquakes, floods, extreme weather, tsunamis).

The main objective of NARSIS was to bring sound contributions to the safety assessment methodologies by reviewing, analysing and developing/improving some related aspects. The main challenges specifically addressed by NARSIS were the following:

- A better characterization and assessment of external natural hazard events (single, combined, cascading), together with a re-evaluation of screening criteria for main critical NPP Systems, Structures & Components (SSC);
- A better assessment of the fragility of NPP Systems, Structures & Components (SSC), to include functional losses, cumulative effects (e.g. seismic aftershocks, thermal fatigue & earthquakes, etc.), ageing effects, interactions, human aspects;
- A better risk integration, to support the risk-informed decision making and a risk metrics comparison within extended PSA;
- A suitable uncertainty treatment for parameters, models and completeness issues;
- An improvement of the processing and integration of expert-based information within PSA, based on modern uncertainty theories, to represent in flexible manner experts' judgments and to aggregate them.

The global concept of the project consisted in providing a scientific framework, to address:

- Theoretical improvements in natural hazards assessment and their impacts, including the evaluation of the uncertainties and the reduction of subjectivity in expert judgments;
- Verification of the applicability of the findings in the frame of the safety assessment through adequate strategies for simulations (e.g. metamodelling) and finally,
- Development and application at the demonstration level of a dedicated decision-support tool for severe accident management.

In the following sections, we give an overview of the main achievements produced by the project.

THE NARSIS MULTI-HAZARD FRAMEWORK

Existing safety analyses for NPP are generally based on single external hazards in terms of the external loading applied on SSC. A first key objective of the NARSIS project was to develop an integrated Multi-Hazard (MH) framework, able to quantify and assess primary and secondary hazards including cascading effects as well as uncertainty, in order to allow studying the consequences of combinations of potential well-characterised physical threats due to different external hazards and scenarios within a nuclear safety assessment process. Within the project, it was decided to focus on some external hazards identified as priorities by the PSA End-Users community in the ASAMPSA-E project: earthquakes, floods, tsunamis and extreme weather. A second objective was to provide recommendations for use of the framework.

Implementation and Key Findings

As determined by the ASAMPSA-E project, over 70 external hazards from various origins exist. These hazard types can occur singularly with direct or indirect impacts upon NPPs or as various MH scenarios. Some natural hazard types are influenced by other ones either directly (induced second hazard), or due to a common root cause (causally correlated), and some have little correlation with the others (e.g., volcanoes with heatwaves) and indeed some are mutually exclusive (e.g., high water level and low water level). Coincidental hazards are events that occur simultaneously but are independent. Indeed, each of these hazard-type interactions needs to be examined in a MH assessment. The definition of hazards was the first important step to characterising which potential events could impact NPPs. A very important concept associated with each hazard was the duration of each event.

Many historical single and MH events were reviewed (NARSIS Del1.1, 2018), including large events (e.g., Tohoku 2011 earthquake and tsunami) which will have a long-lasting impact on the nuclear industry. Over 60 natural hazard events were identified affecting NPPs in Europe, but in most cases, the damage was not extensive. However, many more events not affecting NPPs were identified from history. In fact, for earthquakes, 30% of all fatalities have not been from shaking but from secondary effects such as tsunami or landslides. Such events are important for calibration of any NPP MH assessment.

The key design parameters for earthquake, flood and precipitation were also identified from the review of the stress tests for the European NPPs, using the national and individual plant reports for each NPP. The MH aspects were however not touched upon in nearly all cases, thus the need for NARSIS (Haecker et al., 2019). As for the key hazards identified to affect NPPs across Europe (earthquakes, tsunami and waves, extreme weather effects, flooding), empirical data for Europe were collected and examined as well as a discussion of empirical events collected from various scientific papers, projects and industry briefs (NARSIS Del1.1, 2018). In addition, the improvement of existing Probabilistic Hazard Assessment methodologies for tsunami, extreme weather and flooding (NARSIS Del1.2, 2020; NARSIS Del1.3, 2020) was explored and for each of the single hazard curves, the NPP components were examined in order to ensure that relevant hazard parameters were provided for each hazard in the final framework.

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

The main goal being to come up with a software framework, a full review of the existing open-source / open-access software packages was performed, as to their ability to model single perils, to address singular / combined hazards and cascades, but also the potential impact on supply and infrastructure (road access, power supply, water supply, etc.) in which the NPP is embedded and on which its functionality depends. Very few software packages deal with multi-hazards and none of them deal directly with event trees. The sensitivity of the model assumptions leading to the hazard curves were also gleaned.

Despite the various methodologies (e.g., multivariate analysis, MH scenarios and combinations of curves), existing at global, regional and local scales, there has been no significant study dealing with an empirical-analytical hands-on approach for NPPs (ASAMPSA-E did provide some background but no model). So the 3-level MATRIX framework (Liu et al., 2015) which proposes qualitative, semi-quantitative and quantitative MH analyses, was a good candidate for NARSIS, to be complemented and adapted to meet the NPP specific nature. The **final NARSIS framework** (NARSIS Del1.7, 2021) includes **five successive levels for assessment**, to be used as part of the steps related to Initiating Events and Screening (deterministic or probabilistic) analyses in extended PSA: **(0)** single hazard assessment through standard practice or improved methods; **(1)** MH assessment scoping through potential site specific hazards; **(2)** MH interaction matrix and scoring; **(3)** Modellability matrix; **(4)** Quantitative analysis of multiple hazard probabilities. This methodology was implemented in the open-source open-access NARSIS Multi-Hazard Explorer tool (NARSIS Del1.8, 2021). The various pathways for analysis of MH scenarios using the NARSIS framework (Level 1 to 4) are depicted in Figure 1.

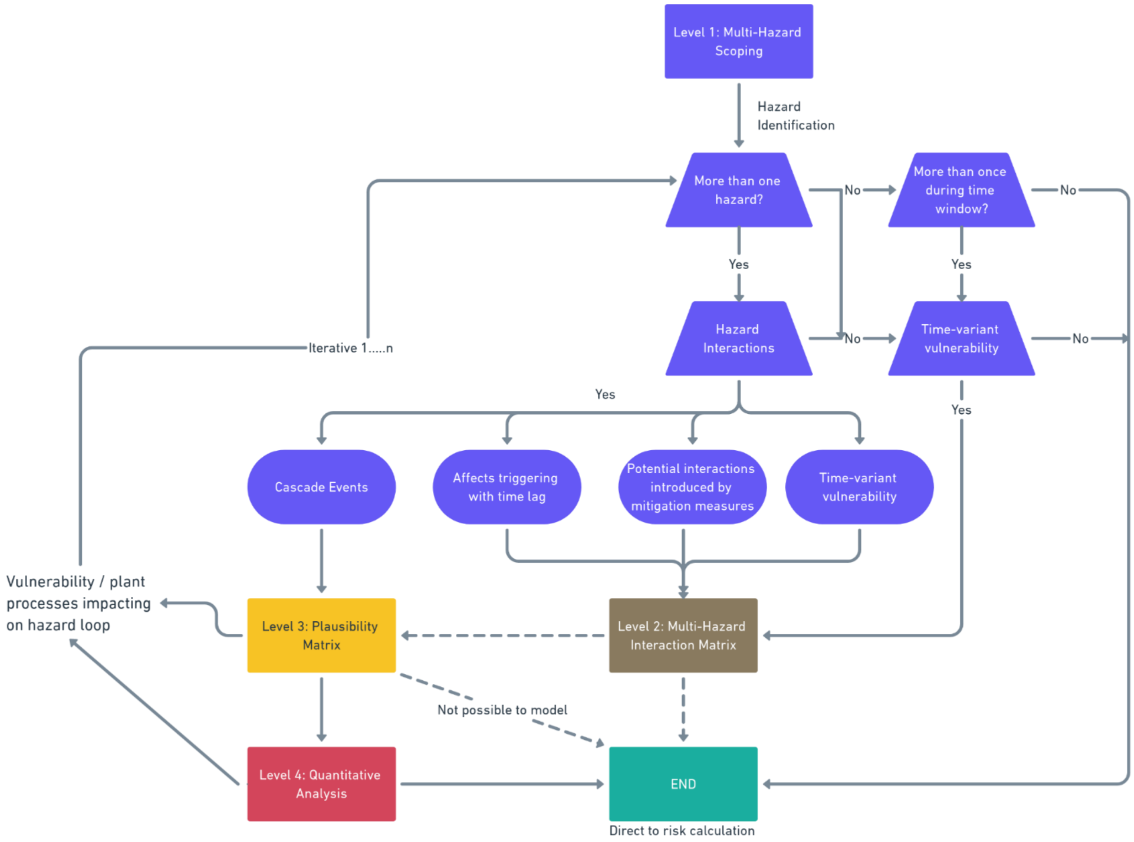

Figure 1. Overview of the various pathways for analysis of MH scenarios in the NARSIS framework (for input into PSA).

Recommendation for use

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

The step from single to MH 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 MH scenarios are the most realistic.

The last steps of the integrated framework enables to assess the modellability of the MH scenario and proceed to the numerical calculations of the occurrence probability of the given scenario and of its effects on the main critical SSC selected for analysis. In case of independent single natural hazards, the NARSIS MHE software can be used as well.

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

FRAGILITY ASSESSMENT IN A MULTI-HAZARD CONTEXT

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

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

In NARSIS, the first step was hence to determine the safety significance of the most critical SSC in NPP systems, in order to focus on the components that deserve in-depth fragility assessment. The screening and selection process was based on risk-informed criteria using different quantitative importance measures (e.g. the Fussell-Vesely) depicting the change of the system unavailability when the contributor’s failure probability is set to 0 or 1. Then, various numerical models and approaches were investigated in order to integrate cumulative effects such as ageing effects and successive loadings or soil-structure interactions.

Regarding seismic fragility assessment of SSCs in case of aged components, a deterministic approach was adopted and several 3D finite-element simulations were performed on the NARSIS reference plant model and components (see, model on Figure 2). Regarding the ageing effects, structural degradations due to accelerated flow corrosion, creep and time and/or temperature material properties degradation, were among the key factors assessed to obtain a realistic evaluation of the class-1 safety structures (specifically reactor buildings and primary piping system). Thermo-mechanical analyses were performed on the primary piping system, considering operating conditions and subjected to homogeneous as well as heterogeneous (either generalized or localised) wall thinning, assumed to represent ageing effects. The seismic evaluation was then performed considering 50 different ATH records and different ageing stages. This approach allowed to derive the residual capacity as well as the residual life of SSC.

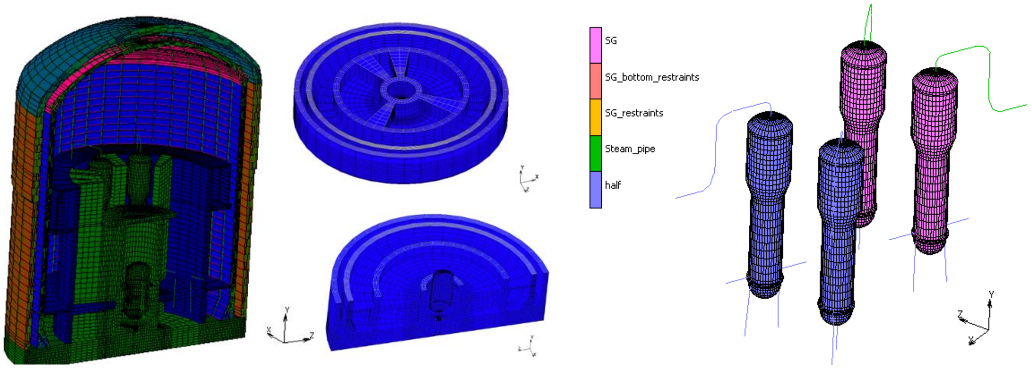

Figure 2. Overview of the finite-element model of the containment system (left) and steam generators with pipe (right)

Finally, the benefits of using multiple IMs (referred to as vector-valued IMs) for fragility assessment of SSC against single (earthquake) and MH natural events, were investigated. Such a concept is especially suited to the case of seismic fragility assessment, where a strong-motion record may be represented by a wide range of parameters such as peak amplitude, frequency content or duration (Gehl et al., 2013). For multiple hazards, each IM can represent the loading level of a different hazard and the consideration of all IMs provides the means to quantify the probability of damage for MH scenarios. Such an approach relies on the combination of failure modes due to single hazard loadings and on the assessment of cumulative hazard effects on the studied system (Gehl & D'Ayala, 2016).

In the case of seismic loading, the approximation a complete waveform (e.g., acceleration time history) by a single IM leads to an aleatory type of uncertainty, sometimes referred to as "record-to-record variability" (i.e., two different waveforms may have the same IM but results in very different structural responses). Therefore, selecting the most adequate IM for fragility functions should obey the following criteria: (i) *efficiency* (IM ability to induce a low dispersion in the distribution of the component response); (ii) *sufficiency* (IM ability to "carry" the earthquake features); (iii) *computability* (ability to quantify the IM accurately with current ground-motion models). In NARSIS, a list of computable IMs was pre-selected and evaluated through a *proficiency* indicator, which combines practicality and efficiency criteria.

The combination of two IMs (e.g., the Peak Ground Acceleration - PGA, and the spectral acceleration - SA) at a given period T, provides a higher proficiency indicator than when considering the single IMs separately. This is confirmed by deriving the corresponding vector-valued fragility function (i.e., the fragility surface) and by comparing it to the single-IM fragility curve (see, Figure 3). Taking advantage of the PGA-SA(T) distribution of the data points, "slices" of the fragility surface were extracted for various percentile values and were plotted as a function of SA(T) only. An interpretation of the resulting graphical construction shown in Figure 3 leads to an estimation of the part of the variance that is transferred from the aleatory component (i.e., record-to-record variability) to the epistemic component when using a vector-valued fragility function: in the present example, it was found that around 20% of the total variance may be reduced by introducing the combination of two IMs.

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

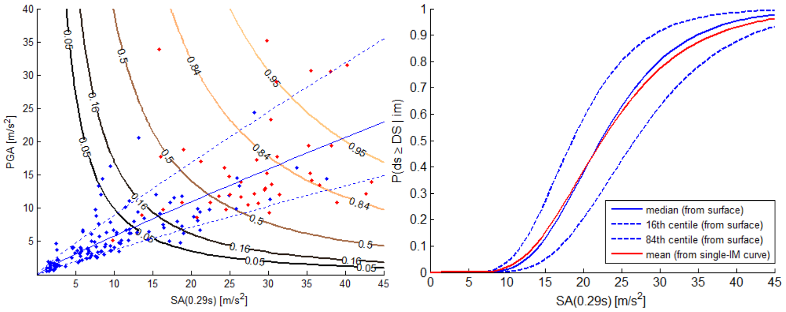

Figure 3. Example of a fragility surface (left) and equivalent fragility curves (right), the solid blue line representing the median distribution and the dashed blue lines the 16%-84% confidence intervals.

THE MULTI-RISK INTEGRATION FRAMEWORK FOR SAFETY ANALYSIS

In NARSIS, the aim was to improve the integration of external hazards and their consequences with existing state-of-the-art risk assessment methodologies in the industry, by investigating, further developing, applying and comparing different approaches (e.g. the Bayesian Networks - BN) capabilities in safety assessment. Constraining uncertainty on modelling results before integration was an ultimate goal, identifying the most influential sources and prioritising those which should be reduced accordingly.

The Bayesian Networks integration approach

Based on the review of various risk integration methods (NARSIS Del3.1, 2018), BN were identified as a suitable framework for considering multiple external hazards and consequences. A specific accident scenario was first selected for the reference NARSIS plant model, postulating a loss of offsite power (LOOP) as initiating event, followed by one or more external hazard events, and assuming various situations: e.g., a LOOP for an extended time with Emergency Diesel Generators (EDG) and/or Ultimate Diesel Generators potential failures leading to a partial or total Station BlackOut (SBO) situation; Secondary Cooldown (SCD) system actuation in case of partial SBO, etc.

Then, various subnetworks (BN) were developed for technical aspects as well as human and organisational aspects, including their interactions with external hazards. The flow chart of this integration is presented in Figure 4. The vector-based fragility of components was modelled within the technical BN, allowing for the inclusion of more than one IM for each hazard, within a MH risk BN. Regarding human aspects, a human BN was developed to estimate human error probability (HEP) for an operator action during event progression from SBO to SCD within the accident scenario (NARSIS Del3.2, 2021). A new BN-SLIM approach was implemented for HEP estimation and compared to the existing BN-SPARH method (Abrishami et al., 2020). The probabilities of performance shaping factors (PSFs) and their influence on the operator's failure to gather information (I), make decisions (D) and take actions (A) were obtained via structured expert judgement elicitation (Figure 5). The coupling of this approach with structured expert judgement elicitation to populate the probabilities within the BN, highlighted its applicability in data-scarce NPP risk problems.

The postulated accident scenario was used to compare BN with fault tree (FT) analyses currently widely used in traditional PSA. These methods were compared under various risk assessment aspects such as top event probability estimation, failure diagnostics, importance measures, the incorporation of multi-state variables and statistical dependencies. A new approach to common cause failure (CCF) modelling in BN, based on correlation between component failures, was developed and compared with the Multiple Greek Letter (MGL) model which is often used in PSA (see, NARSIS Del3.4, 2022). This new approach showed several advantages over conventional parametric models, especially in asymmetric systems. It can also simplify visualisation of BNs for complex systems with many redundancies.

For complex (sub-)systems, BN were used as surrogate models for advanced numerical methods, modelling the reliability of components/sub-systems, in order to substantially reduce the computational effort and to provide a direct link to a larger BN, estimating the overall system risk. This was applied to the reliability assessment of flood control dikes.

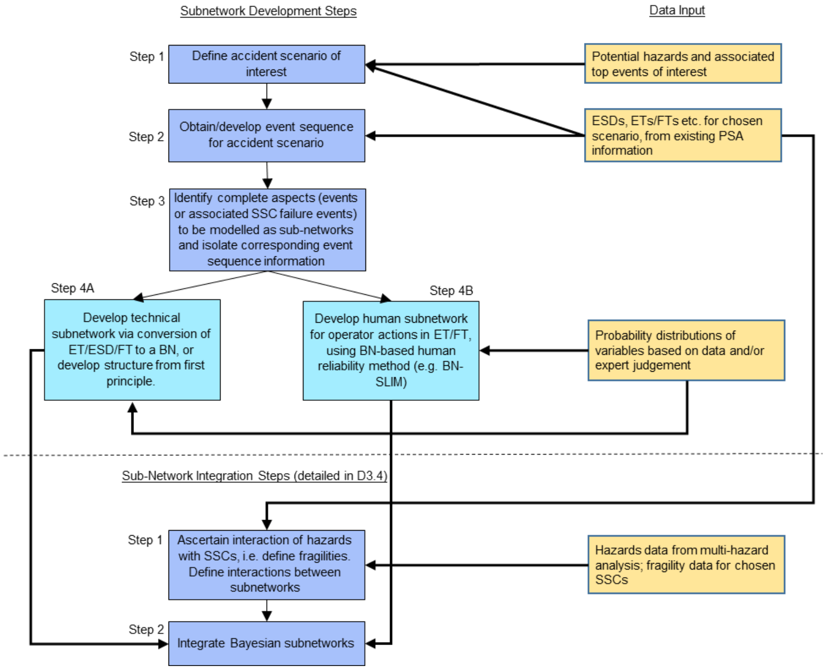

Figure 4. Generic methodology for the development of Bayesian subnetworks for a NPP subjected to external hazards (NARSIS Del3.2, 2021).

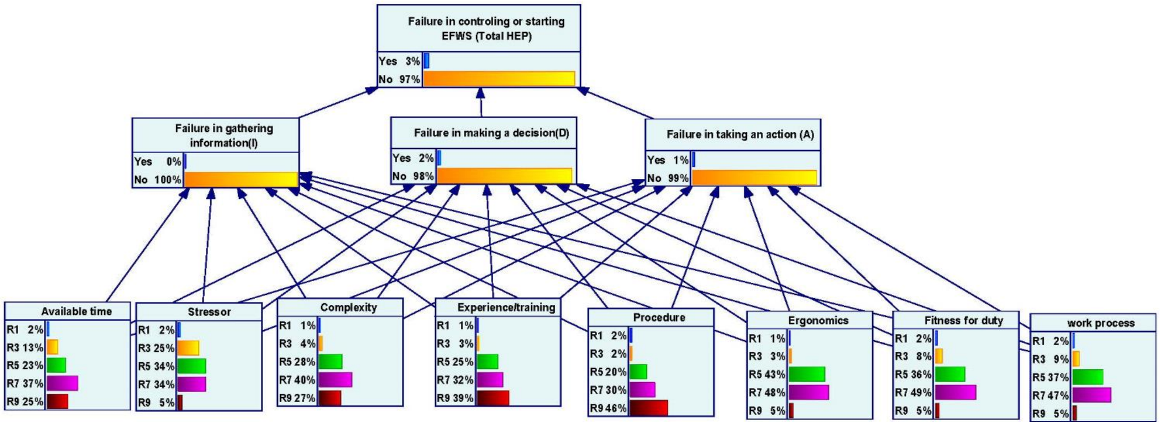

Figure 5. BN-SLIM with the probabilistic evaluation of performance shaping factors, in HEP estimation (NARSIS Del3.2, 2021).

Constraining uncertainties

Many complex models were used in NARSIS, to characterise the physical external threats and the fragility of SSC. In practice, this means many sources of uncertainty related to data, parameters, model assumptions, etc. Building upon the best practices for uncertainty assessment (de Rocquigny et al. 2008), a special attention was paid to characterise uncertainty pervading NARSIS models by dealing with three specificities: the use of BN modelling, the question of components' fragility and the use of expert-based information.

Regarding uncertainty in BN modelling, the main sources were reviewed, identifying uncertainties related to the parameters of the Conditional Probability Model as a key aspect (see, NARSIS Del3.3, 2020), and developing a new approach named "Boosted Beta Regression" (Rohmer & Gehl, 2020). This approach can be applied to any kind of BN (i.e., discrete, Gaussian or hybrid), and is robust to the number of parameters. Regarding fragility assessment, a Bayesian updating framework was proposed, by combining an Artificial Neural Network, an adaptive training algorithm and an amplification-factor-based construction of the likelihood function (Wang et al., 2018; NARSIS Del3.3, 2020). The framework allows for an improved seismic capacity estimation and possible reduced uncertainties based on information from experience feedback. This framework was applied to the KARISMA[1] benchmark, using damage data collected from the field observations and the database of the Seismic Qualification Utility Group. Results showed that the proposed approach allows to reduce epistemic uncertainties (i.e. related to the lack of knowledge) in the fragility curves. Finally, regarding expert-based information, the applicability of new approaches / procedures taking advantages of new uncertainty theories (see e.g., Dubois & Guyonnet, 2011) were extensively explored either for: (i) the modelling of expert knowledge and reproducing expert-like reasoning based on fuzzy expert systems or (ii) the evaluation of expert-based information to complement the classical model of Cooke (NARSIS Del3.7, 2020; Rohmer & Chojnacki, 2021). In this latter case, two aspects were investigated using 33 expert datasets: (i) robustness to the set of calibration questions used to estimate the scores, i.e. whether the best and worst performing expert differs; (ii) forecast performance, i.e. the degree of accuracy and informativeness of the derived forecast intervals.

CONCLUSION

The proposed MH framework is very plant specific, and although the methodology can screen all hazard types along the lines of the modified single hazards explored within ASAMPSA-E, and all the scenarios, there are still some combinations, which may be missed due to specific fragility loops, and/or dynamic hazard loops. Hence, the MH framework needs further calibration and is susceptible to be updated at completion of the NARSIS project. It is also worth noticing that expert judgement and engineers specialists in many fields (seismologists, hydraulics, meteorological, statistics, etc.) are still necessary all along the process, from the hazard characterisation to the MH scenarios quantitative assessments. The methodologies and developments offered by NARSIS with respect to MH risk integration and assessment can all be used within a PSA. Each has advantages and disadvantages, and this work adds to the available tools which can be used to analyse and communicate on safety. Some methods (e.g., BN) can be used as advanced versions of standard tools, whereas others can be used to investigate specific aspects and reduce uncertainties. Given the large variety of decision-making situations, finding a single appropriate framework appears to be debatable, and it is beneficial to take advantages of the strengths of multiple approaches to capture different types of information and knowledge important to inform decision-making. With the new developments for uncertainty characterisation, any practitioner of NARSIS is equipped with efficient sensitivity analysis tools to identify most influential sources of uncertainty and to set up prioritisation for reducing them. These developments, though dedicated to the specific aspects addressed within NARSIS, are of interest for any practitioners that are confronted with uncertainty analysis in safety assessments as shown by our applications to multiple and diverse real cases. In case of modelling of operator/human actions, the human failure probability for these actions can now be assessed and included in the study. Finally, a particular result is for the treatment of expert-based information using the tools of new uncertainty theories.

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