



## A framework for the system-of-systems analysis of the risk for a safety-critical plant exposed to external events

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### ABSTRACT

We consider a critical plant exposed to risk from external events. We propose an original framework of analysis, which extends the boundaries of the study to the interdependent infrastructures which support the plant. For the purpose of clearly illustrating the conceptual framework of system-of-systems analysis, we work out a case study of seismic risk for a nuclear power plant embedded in the connected power and water distribution, and transportation networks which support its operation. The technical details of the systems considered (including the nuclear power plant) are highly simplified, in order to preserve the purpose of illustrating the conceptual, methodological framework of analysis. Yet, as an example of the approaches that can be used to perform the analysis within the proposed framework, we consider the Muir Web as system analysis tool to build the system-of-systems model and Monte Carlo simulation for the quantitative evaluation of the model. The numerical exercise, albeit performed on a simplified case study, serves the purpose of showing the opportunity of accounting for the contribution of the interdependent infrastructure systems to the safety of a critical plant. This is relevant as it can lead to considerations with respect to the decision making related to safety critical-issues.

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### 1. Introduction

The focus of this work is to look at the safety of a critical plant challenged by the occurrence of an external event, like earthquake, flooding, high wind, fire, lightning, volcanic eruption [1]. We assume that properly designed and dimensioned, “internal” emergency devices are available to assure safety of the critical plant upon such disturbances, even in the case of unavailability of the infrastructure services. However, accidental events in the industrial history, e.g., the recent Fukushima disaster [2], show that the post-accident assurance of the full or partial safety of a critical plant in the emergency conditions of an external disastrous event may also need to resort to exceptional recovery means and actions, which need to be supported by the infrastructures connected to the critical plant. In other words, upon the occurrence of the destructive event, the surrounding environment may or may not be left in the conditions to provide “emergency assistance” to the critical plant. Indeed, considering an external event which is spatially distributed, its impact may not affect only the critical plant itself but also the areas around it,

with possible damages to the interdependent infrastructures that may or may not be capable of providing the services needed for keeping or restoring the safety of the critical plant.

With these considerations, we propose to extend the boundaries of the analysis for evaluating its safety by adopting a “system-of-systems” framework of analysis [3–9], which includes the interdependent infrastructures connected to the plant, in addition to its internal emergency devices, and thus examines also the “resilience” properties offered from the overall structure of the system of systems in which the plant is embedded. For the purpose of illustrating the concepts underlying the extended framework, as quantitative indicator we consider the probability that a critical plant remains or not in a “safe state” upon the occurrence of an external event. Safe state is here used to indicate that the plant is in a condition that does not cause health and/or environmental damages.

To provide an example of application of the proposed framework, we consider a case study regarding the occurrence of an earthquake (the external event) impacting on a system of systems which contains a nuclear power plant (the critical plant) that is provided with the needed emergency infrastructure systems. For exemplary purposes, the framework extends the analysis to the power and water distribution, and to the transportation networks (the interdependent infrastructure systems) that can provide services necessary for keeping or restoring the safety of the

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critical plant. The case study is used only to illustrate the concepts behind the framework of analysis under a system-of-systems viewpoint: for this reason, it is fictitious and admittedly highly simplified in the technical aspects (including those of the nuclear power plant and its safety systems) and strong, possibly at times not too realistic, assumptions are made to keep the focus on the methodological framework. In spite of this, for completeness the modeling and numerical evaluation are carried out by resorting to powerful methods of system analysis and stochastic simulation: Muir Web [10] and Monte Carlo simulation [11–13].

Muir Web is a system analysis technique to model a complex system and the relationships among its elements. In the context of ecological human community, in which it has been first introduced [10], traditionally only the major interactions are taken into account in the system modeling: for example, with reference to the food chain, only the connections between predator and prey are usually considered, whereas other relevant and influencing relationships exist between organisms, e.g., one species may take cover for another, and other factors contribute to the food chain, e.g., abiotic elements like water, sun, soil, rainfall, wind [10]. By the representative power of Muir Web, the traditional picture of dependencies is extended through a graph where the nodes represent all the system elements (e.g., species and abiotic factors in the ecological case) and the edges represent their dependency structure.

The concept of Muir Web has been recently applied also to infrastructure systems, exploiting some similarities which exist between the ecological and the infrastructure networks [14]: both are large scale systems with complex interactions and can fail when an external event occurs. In the case of infrastructure systems, the nodes of the web are system components, e.g., a pump, and other factors which influence the infrastructure state, e.g., a stable soil with respect to seismic hazard.

In the case study worked out in this paper, the assessment is performed in two main steps: first, a conceptual map in the form of a Muir Web is built to represent all the dependencies and interdependencies among the components of the infrastructure systems connected to the nuclear power plant; then, Monte Carlo simulation is applied to compute the probability that the nuclear power plant enters in an unsafe state, accounting for the contributions of both the internal emergency devices and the connected infrastructures to support the safety of the critical plant. An analysis is also made to find how much the interdependencies would affect the safety of the nuclear power plant.

The remainder of the paper is organized as follows. In Section 2, the basic concepts of External Event Risk Assessment are introduced, with some specifics of Seismic Probabilistic Risk Assessment (SPRA) for positioning the illustrative case study used to exemplify the methodology; in Section 3, the Monte Carlo simulation framework for SPRA is described for providing the basic ground of the quantification technique used in the case study; in Section 4, the complete assessment of the case study by Muir Web and Monte Carlo simulation is presented, and the results discussed; in Section 5, conclusions and reflections are shared and future developments are provided.

## 2. Natural External Event Risk Assessment

The framework of the analysis considers natural external events as hazard inputs. They can include earthquake, flooding, high wind, fire, lightning, volcanic eruption [1]. The common characteristics of these hazards are the large-scale impacts on the environment and the considerable amount of uncertainty related with their occurrence and their intensity.

To include them in the safety analysis of a critical plant, the following steps should be performed [1]:

- a. Assessment of the frequency of the hazards (i.e., estimation of the frequency of exceedance of particular intensities) and analysis of the loads associated;
- b. Analysis of the plant response to the hazards (i.e., fragilities);
- c. Analysis of the impacts of the hazards on the plant.

To proceed in the analyses, properties and parameters of the hazards should be defined. For example, for seismic hazard, parameters like intensity of the earthquake, ground motion and frequency content (e.g., response spectrum) should be defined; for flooding, relevant parameters include water level of the river/lake, duration of flood and water velocity; for high winds, the dynamic loads from gusts and rotation velocities from tornadoes should be given.

In the present paper, the seismic hazard has been taken into account within a framework of Seismic Probabilistic Risk Assessment (SPRA) based on three parts [15,16]:

- a. Seismic Hazard Analysis to compute the probabilities of occurrence of different levels of earthquake ground motion at a site of interest.
- b. Seismic Fragility Evaluation to identify the seismic capacity of a component in terms of its conditional probability of failure for any given ground motion level.
- c. System Analysis to integrate the outputs of the hazard and fragility analyses for evaluating the impacts of the earthquake on the infrastructure of interest.

The first part, which is traditionally developed as Probabilistic Seismic Hazard Analysis (PSHA), consists of four procedural steps [15–17]:

- 1) Identification and characterization of the earthquake source;
- 2) Definition of the earthquake recurrence relationship, i.e., the annual frequency of occurrence of a given magnitude event for each source, typically described by the Gutenberg–Richter law [18] that implies a double-truncated exponential distribution for the magnitude<sup>1</sup> [21,22]:

$$F_M(m) = \frac{1 - e^{-\beta(m - m_{min})}}{1 - e^{-\beta(m_{max} - m_{min})}} \quad (1)$$

where  $\beta$  represents the relative frequency of smaller to larger events and  $m_{max}$  and  $m_{min}$  are the upper and lower bounds of the magnitude, respectively, that avoid the high values which are unrealistic and the low values that are negligible.

- 3) Formulation of the ground motion attenuation relationship that identifies the ground motion value at the site of interest, e.g., the peak ground acceleration, given the source-to-site distance and the magnitude. The higher the distance from the source, the lower is the ground motion value. The following relationship described by Ambraseys [23] has been embraced in this paper:

$$\log_{10} z' = C_1 + C_2 m + (C_3 + C_4 m) \times \log_{10} \sqrt{r^2 + C_5^2} + C_6 S_s + C_7 S_A + C_8 F_N + C_9 F_T + C_{10} F_0 \quad (2)$$

<sup>1</sup> The magnitude scale typically used is the moment magnitude defined by Kanamori [19]. For medium size earthquakes it is similar to the Richter values [20].

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