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# A PROBABILISTIC FRAMEWORK TO ASSESS MULTI-HAZARD RISKS CONSIDERING STRUCTURES SUBJECTED TO CONCURRENT AND SEQUENTIAL HAZARDS

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**Abstract.** Critical infrastructure systems are exposed to various natural hazards. These hazards may be induced by events such as earthquakes and hurricanes that can occur concurrently or in sufficiently close succession that the effects of one hazard are not mitigated before the occurrence of the next hazard. The impacts of these hazards can result in component- and system-level failures and significant economic loss. Although single-hazard probabilistic risk assessment approaches have been extensively used to study each of these hazards, there is a limited number of studies that have attempted to analyze the relationships between multiple hazards and assess their risks probabilistically.
This paper (extended abstract) aims to 1) summarize the findings of a literature review focused on multi-hazard fragility modeling, considering the interactions between wind and ground motion hazards, and 2) describe ongoing efforts to create a Bayesian Network (BN) framework for assessing multi-hazard risk that affects a spatially distributed system. The proposed framework is capable of modeling the concurrent and sequential relationships of the hazards and assessing their impacts on the performance of the distributed system.

## 1. INTRODUCTION

The impacts of hazards occurring concurrently or sequentially can result in amplified loads on infrastructure and increased system-level impacts. Understanding structural behavior under multiple hazards (e.g., earthquake-induced ground shaking and tropical cyclone-induced winds) is essential for comprehensive risk assessments, as traditional single-hazard approaches cannot capture compounded effects.

This paper (extended abstract) first summarizes the results of a literature review on multi-hazard fragility assessments considering wind and ground motion hazards. The review highlights several gaps in the existing state of knowledge. Currently, few studies are available that develop fragility functions that account for either accumulated or concurrent hazard effects, considering hazards such as strong winds and ground motions. This poses a challenge for accurate risk estimation and supporting informed decision-making for infrastructure resilience under multi-hazard conditions.

Next, this paper summarizes the results of ongoing efforts to develop a Bayesian Network (BN) framework for multi-hazard risk assessment models for spatially-distributed infrastructure, adapting it to the context of systems subject to hurricane-induced winds and earthquake-induced ground motion. The presented BN framework probabilistically models the concurrent and sequential relationships between winds and ground motions in hazard, fragility, and system performance modules.

### 1.1. Literature review

The reviewed literature employs various methodologies for developing fragility curves and formulating multi-hazard assessments. These non-unified approaches can complicate the understanding and implementation of multi-hazard risk analysis.

Studies on wind and ground motion in multi-hazard analysis primarily fall into two groups. The first group accounts for sequential or concurrent hazard effects by incorporating cumulative damage or joint impacts into the fragility assessment. The second group includes studies that consider both hazards but do not account for their interactions when evaluating their impacts on structures (i.e., the fragility of the structure to one hazard does not change given the occurrence of the other hazard).

In the first category, we identified several studies that incorporate interactions between wind and ground motion in fragility assessments. For example, [1] analyzed approximately concurrent loading from typhoon winds and ground motions over a 220-second duration. Focusing on a single transmission tower, they assess how wind and ground motion load exposure influences the collapse probability of the structure. As another example, [2] investigated multi-hazard fragility analysis of a tower subjected to simultaneous ground motion and wind loads, coupled with wind fatigue analysis.

In the second group, studies treat wind and ground motion separately in fragility assessments, such that the studies do not explicitly consider the interactions between hazards and their impacts on the structure. For example, [3] used separate fragility functions to analyze bridge performance during earthquake and hurricane scenarios. Fadel Miguel et al. (2023) ([4]) also conducted a multi-hazard assessment for a transmission line system subjected to non-concurrent wind and ground motion forces.

Salman and Li (2018) ([5]) analyzed the effectiveness of multi-hazard risk mitigation strategies for a power system subjected to earthquake and hurricane events, where they assumed no interaction among hazards and their imposed loads on the system. Y. Li and Ellingwood (2009) ([6]) presented a comparative risk assessment framework focused on wood-frame residential buildings exposed to ground motion and wind during their service life. Their framework evaluates the risk from wind and earthquake-induced loads by considering an independent relationship between hazards.

Our research team is currently undertaking efforts to develop strategies to address gaps within the existing literature related to multi-hazard fragility assessment by leveraging Bayesian strategies to visualize and model dependencies. In addition, in parallel with these efforts focused on fragility modelling for multi-hazard contexts, we are working to develop a Bayesian Network (BN) framework to obtain a traceable and unified probabilistic multi-hazard risk analysis model focusing on earthquake and hurricane hazards. That framework provides a systematic structure for understanding multi-hazard risk assessment for spatially distributed infrastructure systems, which can benefit from and be leveraged to inform multi-hazard fragility model development activities as described below.

## 2. PROPOSED FRAMEWORK

Bayesian Networks are probabilistic graphical models representing relationships among a series of random variables shown as nodes. The probabilistic dependencies among random variables (nodes) are presented using directed links. In our context focused on probabilistic multi-hazard risk analysis, we use BNs to model the spatial distribution of multiple hazards by accounting for their spatial correlations at multiple locations across a geographic region, and then model the resulting component and system performance.

Figure 2 illustrates the proposed framework considering concurrent relationships between hazards (strong wind speeds and ground motions, in this study). The proposed framework consists of three modules. The first module is the hazard module. This module includes nodes for estimating the seismic and wind hazards at multiple sites based on the identified seismic and wind event sources. Intensity measures are modelled by leveraging or adopting existing BNs for modelling spatially correlated hurricane (e.g., [7], [8], [9]) and earthquake hazards ([10], [11]).

In Figure 1, we show three sites/components ($i = 1,2,3$) at which we want to compute hazard intensities. In the *Hazard Module*, nodes under each hazard (*Hazard 1* and *Hazard 2*) represent intensity measures, $IM_{i,1}$ and $IM_{i,2}$, respectively. The subscript *i* refers to the three considered sites/components and subscripts of 1 and 2 refer to *Hazard 1* and *Hazard 2*, respectively. The nodes outlined in thick black show the intensity measures, and the connected small nodes represent correlated intensity measures residuals.

The second module of Figure 1 is the fragility module, which assesses the concurrent impact of *Hazard 1* and *Hazard 2* loads at the sites of interest. In this module, the EDP nodes refer to the Engineering Demand Parameter, which is adopted from the PEER framework ([12]). Concurrent effects are captured by defining a quantity that enables the superposition of hazards effects (e.g., equivalent static loads). The EDP nodes ($EDP_i$; blue nodes) are dependent on hazard intensity nodes, $IM_{i,1}$ and $IM_{i,2}$, in the hazard module, reflecting the superposition of hazards on measures of structural response. Damage measures ($DM_i$; green nodes), representing the damage caused by jointly imposed hazards, are dependent on the EDPs. As an alternative model formulation, each hazard may be associated with hazard-specific EDPs, and superposition of concurrent effects can occur when quantifying total damage. While not shown in the presented BN, the performance of components may be correlated due to similar designs, degradation, and maintenance. The BN can be extended to capture these effects by adopting and extending the approach outlined by [13], which focused on single-site facilities.

The last module is the system performance module, where each DV node ($DV_i$; orange nodes) represents a decision variable that quantifies system performance outcomes (e.g., damage level or monetary loss). These variables can be used to compute the probability of exceeding specified performance thresholds (such as damage criteria or cost limits) within a given time period. As before, these nodes are dependent on the damage measures ($DM_i$) in the fragility module. The $DV_i$ are connected to the node *Sys*, which represents the performance of the whole system, represented as distributed components/sites.

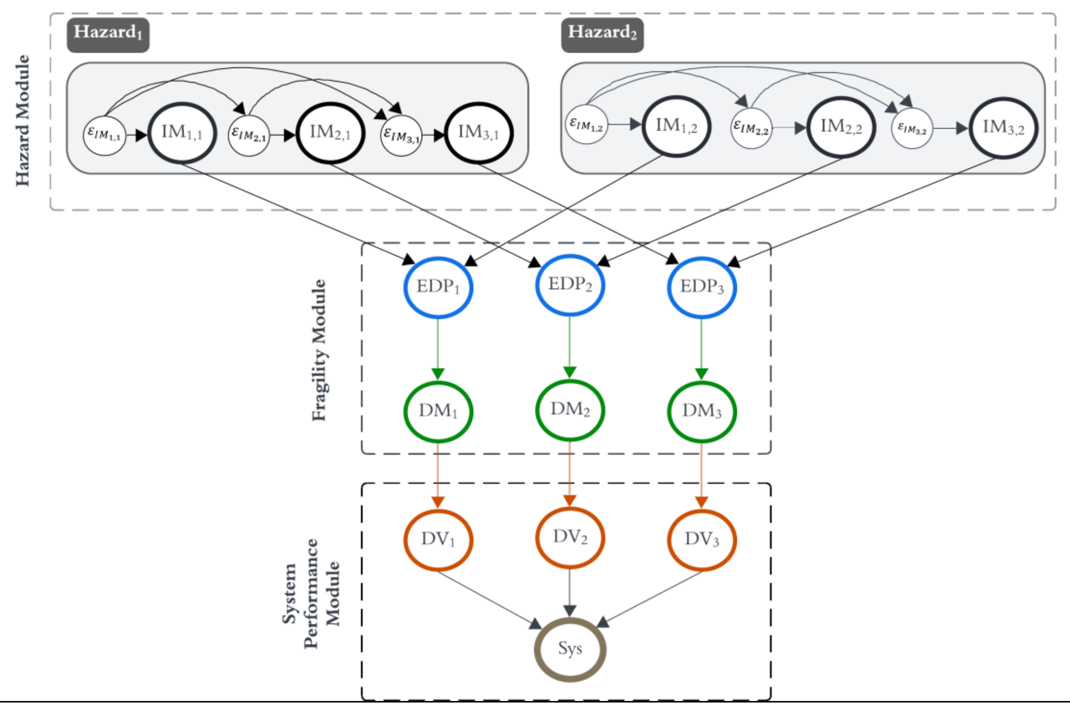


Figure 1. The proposed probabilistic BN for multi-hazard risk analysis considering the concurrent relationship between hazards.

Figure 2 shows the modified framework that reflects a sequential relationship between hazards. The hazard and system performance modules are identical to those explained for the concurrent case (Figure 1). However, in the fragility module, the intensity of the first hazard defines the first set of $EDP_{i,1}$ (solid blue nodes in Figure 2), and then the damage measures for the first hazard ($DM_{i,1}$) are defined dependent on the $EDP_{i,1}$. The occurrence of the second hazard intensity defines the second set of $EDP_{i,2}$ (dashed blue nodes in Figure 3), which are dependent on the second hazard intensity and the first set of $DM_{i,1}$ resultant from the first hazard. The dashed line connecting the damage measures from the first hazard ($DM_{i,1}$) to the $EDP_{i,1}$ nodes from the second hazard indicated that this dependency applies only if the previous damage leads to changes in the second hazard (e.g., previous damage changes the structural damping).

The link connecting the damage measures from the first hazard ($DM_{i,1}$) to those of the second hazard ($DM_{i,2}$) accounts for the accumulated damage. That is, previous damage from the first hazard changes the structure's fragility when faced with the second hazard. As in the previous BN, extension to account for fragility correlation may also be appropriate.

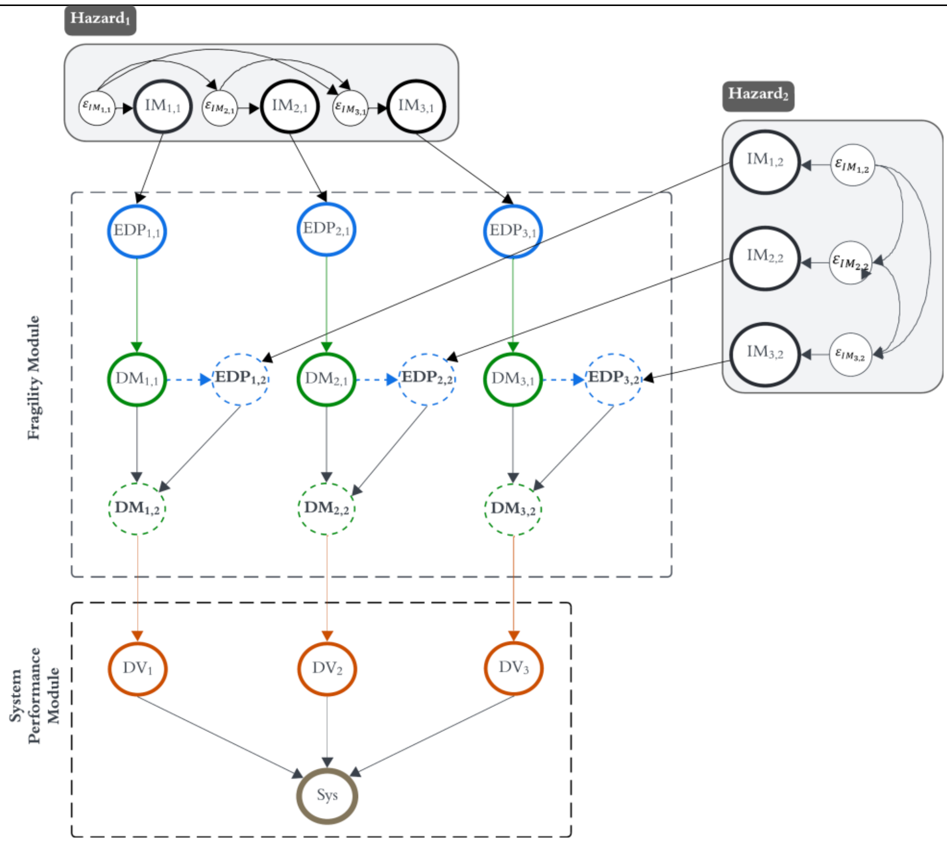


Figure 2. The proposed probabilistic BN for multi-hazard risk analysis considering the sequential relationship between hazards.

The framework's fragility module helps to understand and illustrate how concurrent and sequential relationships of hazards can be translated into engineering demand parameters (EDPs) and damage measures (DMs) within the BN. For a concurrent condition (Figure 1), the module allows for joint fragility modeling by considering the joint hazards' impact on EDPs and consequently on DMs. For a sequential situation (Figure 2), the module allows for conditional fragility modeling by considering the dependencies of EDPs and DMs on the sequential occurrence of hazards.

Work is currently underway to implement the proposed multi-hazard risk assessment framework for spatially distributed systems. The framework will inform and benefit from modeling insights gained from parallel efforts focused on multi-hazard fragility modeling.

## 3. CONCLUSION

This paper (extended abstract) describes ongoing activities associated with two distinct projects, highlighting opportunities for synergies. The first project focuses on multi-hazard fragility modeling, and this extended abstract summarizes insights from a literature review to articulate the current state of knowledge.

The second study aims to develop a BN-based probabilistic framework to assess the multi-hazard risk of concurrent and sequential events on spatially distributed systems such as hurricane-induced strong winds and earthquake-induced ground motions. In the developed BN framework, this characterization is modeled by spatially distributed intensity measures from the considered hazards at three locations. The developed BN framework is flexible in accounting for the superimposed loads due to the concurrent relationship between hazards and the accumulated damage caused by the sequential relationship between hazards. The BN model can transition from assessing the impacts of these hazards, through a fragility module, to evaluating the overall performance of systems composed of multiple spatially distributed components.

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