Use of Bayesian Networks as a Decision Support System for the rapid loss assessment of infrastructure systems

Authors: P. Gehl, F. Cavalieri, P. Franchin, C. Negulescu, K. Meza

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The loss assessment of infrastructure systems has emerged as an essential aspect of the risk and resilience analysis of exposed communities. Predicting the performance loss of critical infrastructure before an event is useful to plan mitigation strategies, while a rapid loss assessment in the short-term (i.e. in the crisis period immediately following the disaster) is especially helpful for emergency responders as it contributes to situational awareness (e.g. knowledge of the areas in urgent need of basic utilities, accessibility of strategic locations, etc.). To this end, conventional approaches to model and simulate infrastructure systems include a probabilistic risk framework, where Monte Carlo simulations are performed from the generation of earthquake events to the computation of the system performance indicators. Alternatively, Bayesian Networks (BNs) have been recently used to structure the links and statistical dependencies between the uncertain variables involved in the analysis chain (e.g. earthquake magnitude and location, ground-motion field, damage state of infrastructure components, response of the system, etc.), thanks to the convenient use of conditional probabilities through Bayes' rule. BNs may be used in a predictive (forward analysis), where all sources of uncertainties are propagated in order to obtain a probabilistic distribution of the variables of interest. On the other hand, BNs also have the ability to perform a diagnostic (backward) analysis, where the prior distribution of given variables is updated from evidence collected on fixed variables (e.g. field observations or measures). The latter property is especially relevant in the context of crisis management, since ex-ante predictive loss models may be updated thanks to the resolution of a BN with incoming evidence, thus contributing to a progressive refinement of the estimated consequences of an earthquake event.

One of the main issues preventing the application of BNs in an operational context resides in the computational complexity, which generates intractable datasets when large real-world systems are considered. Moreover, formulating an exact BN, which depicts all links between variables, requires the implementation of accurate rules between the components' states (i.e. damage states of individual infrastructure systems) and the performance of the whole system. This constraint limits most BN models to a connectivity analysis, while it has been shown that capacity or serviceability analyses provide a much more accurate picture of the situation. Therefore an approximate BN formulation is presented in the present study, in order to allow for a quick and efficient Bayesian updating of predictive models in near-real-time. The proposed approach is based on two distinct steps, as follows:

- Generation of a learning dataset through Monte Carlo simulations: thousands of loss scenarios, accounting for all types of uncertainties, are sampled through infrastructure modelling and simulation tools (e.g. OOFIMS platform from the FP7 SYNER-G project).

- The generated data is used to build a simplified BN formulation, where only the most influent components are kept for the estimation of the system performance. These components are selected through data mining techniques (i.e. supervised learning), and the relation between them and the system performance variable is quantified by counting the Monte Carlo outcomes for each configuration and by computing the associated conditional probability.

The main merit of this approach resides in the selection of a reduced number of influent components, which alleviates the dimensionality curse of the 'components-system' problem. Moreover, the conditional probability table of the system variable is directly built by counting combinations of events in the Monte Carlo, which allows any type of components-system relations to be represented, without necessarily being constrained by strict connectivity rules. This two-step hybrid BN method is applied and validated on a real-world road network in the Pyrenees area (France), where bridges are vulnerable to strong motions and road segments are exposed to earthquake-triggered landslides (more than 70 vulnerable components in total). The generated BN is able to compute the updated distribution of the accessibility loss or of the additional travel time between several points of interest. The inference abilities of the BN are also demonstrated through various hypothetical scenarios, where field observations (e.g. ground-motion records, damage observations) are used to refine the loss estimation of the whole system.