Application of Bayesian Networks in Multi-Hazard Safety Assessment of Nuclear Power Plants

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Nuclear Power Plant Probabilistic Safety Assessment

- Low probability events are a key consideration in multi-hazard safety assessments of nuclear power plants (NPPs)
- Cascading effects from hazards and associated event sequences could potentially have a significant impact on risk estimates.
- The Bayesian network (BN) can act as a framework to consider aforementioned statistical dependencies between various hazards in multi-risk analyses of nuclear power plants.

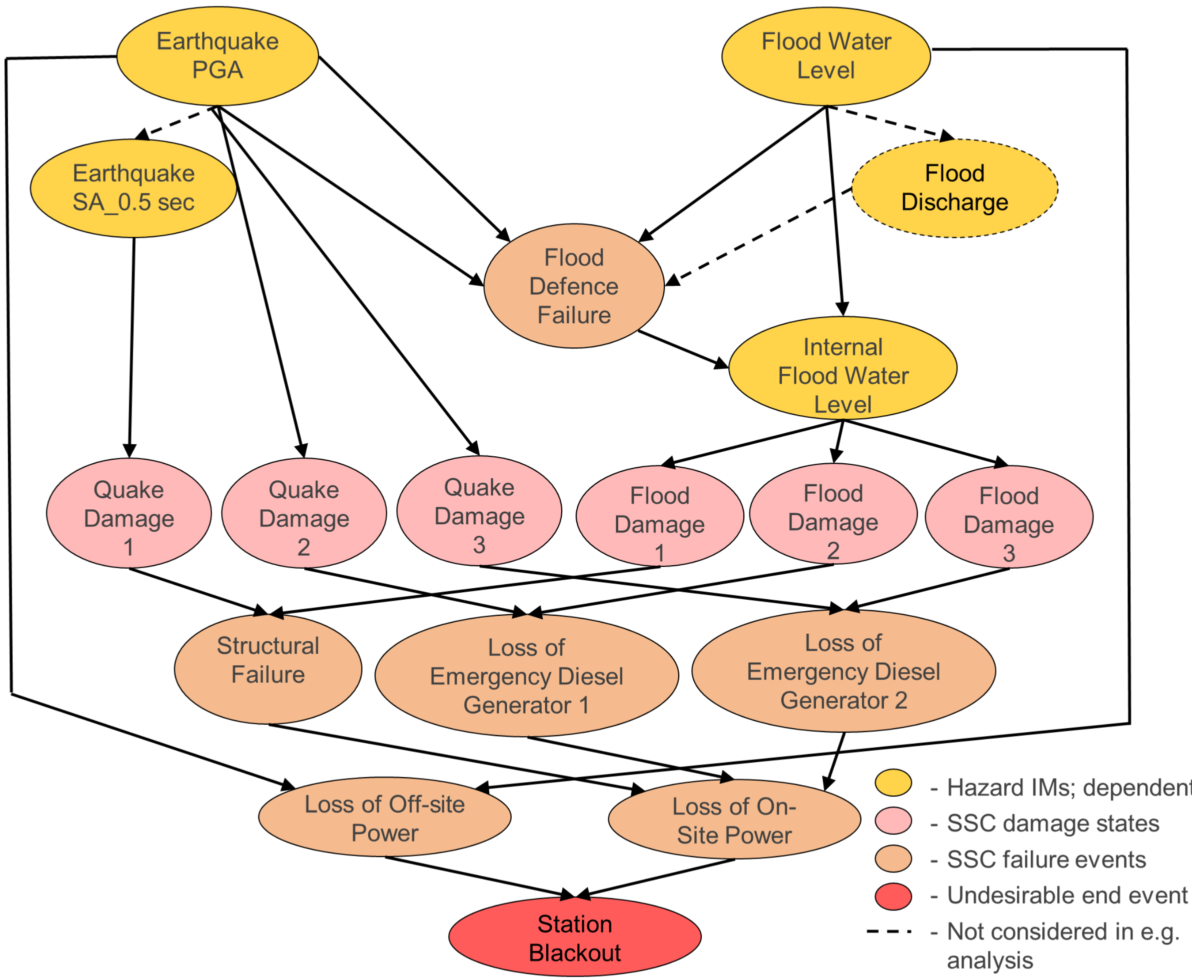
BNs in NPP Risk - Example Implementation

➢ **Simplified BN implementation in Nuclear PSA**

❑ **Simplified scenario used to link hazards, fragilities and NPP end event - Station Blackout - SBO**

❑ **Risk integration procedure developed to move from multi-hazard analysis to final risk estimate**

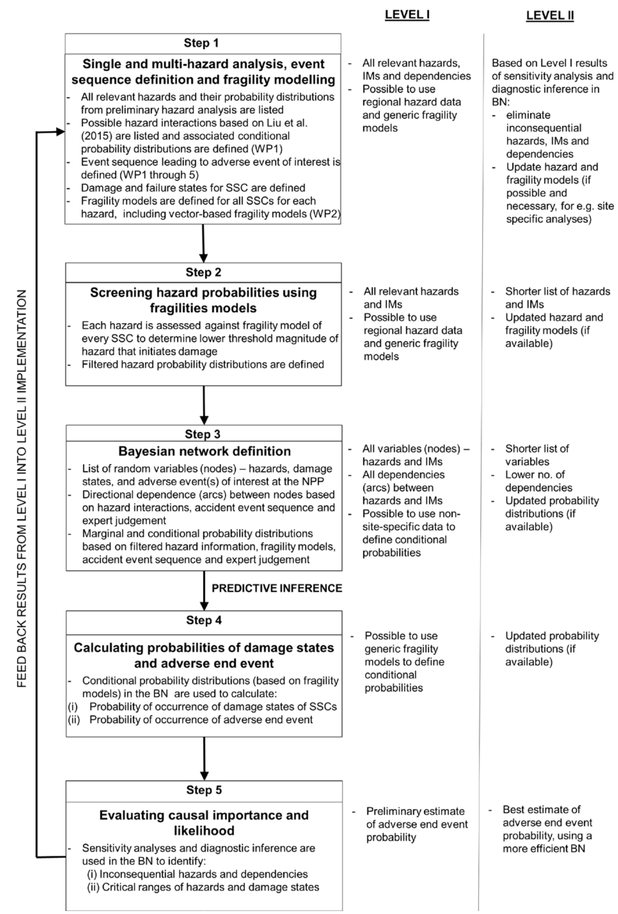
Example Implementation Scenario - SBO



Risk Integration

➢ NARSIS RISK INTEGRATION METHODOLOGY

- ❑ Step-wise, 2-Level procedure
- ❑ Multiple hazards
- ❑ Multiple Intensity Measures
- ❑ Vector-Based Fragilities
- ❑ Sensitivity analysis used to make BN efficient
  - Remove inconsequential hazards and dependencies
- ❑ Diagnostic inference used to fine-tune hazards/fragilities



NARSIS RISK INTEGRATION – Step 1

Step 1

Single and multi-hazard analysis, event sequence definition and fragility modelling

- All relevant hazards and their probability distributions from preliminary hazard analysis are listed
- Possible hazard interactions based on Liu et al. (2015) are listed and associated conditional probability distributions are defined (WP1)
- Event sequence leading to adverse event of interest is defined (WP1 through 5)
- Damage and failure states for SSC are defined
- Fragility models are defined for all SSCs for each hazard, including vector-based fragility models (WP2)

Step 2

LEVEL I

- All relevant hazards, IMs and dependencies
- Possible to use regional hazard data and generic fragility models

LEVEL II

Based on Level I results of sensitivity analysis and diagnostic inference in BN:

- eliminate inconsequential hazards, IMs and dependencies
- Update hazard and fragility models (if possible and necessary, for e.g. site specific analyses)

NARSIS RISK INTEGRATION – Step 2

Step 2

Screening hazard probabilities using fragilities models

- Each hazard is assessed against fragility model of every SSC to determine lower threshold magnitude of hazard that initiates damage
- Filtered hazard probability distributions are defined

Step 3

LEVEL I

- All relevant hazards and IMs
- Possible to use regional hazard data and generic fragility models

LEVEL II

- Shorter list of hazards and IMs
- Updated hazard and fragility models (if available)

NARSIS RISK INTEGRATION – Step 3

Step 3

Bayesian network definition

- List of random variables (nodes) – hazards, damage states, and adverse event(s) of interest at the NPP
- Directional dependence (arcs) between nodes based on hazard interactions, accident event sequence and expert judgement
- Marginal and conditional probability distributions based on filtered hazard information, fragility models, accident event sequence and expert judgement

PREDICTIVE INFERENCE

Step 4

LEVEL I

- All variables (nodes) – hazards and IMs
- All dependencies (arcs) between hazards and IMs
- Possible to use non-site-specific data to define conditional probabilities

LEVEL II

- Shorter list of variables
- Lower no. of dependencies
- Updated probability distributions (if available)

NARSIS RISK INTEGRATION – Step 4

PREDICTIVE INFERENCE

Step 4

Calculating probabilities of damage states and adverse end event

- Conditional probability distributions (based on fragility models) in the BN are used to calculate:
  (i) Probability of occurrence of damage states of SSCs
  (ii) Probability of occurrence of adverse end event

Step 5

LEVEL I

- Possible to use generic fragility models to define conditional probabilities

LEVEL II

- Updated probability distributions (if available)

NARSIS RISK INTEGRATION – Step 5

LEVEL I

LEVEL II

Step 5

Evaluating causal importance and likelihood

- Sensitivity analyses and diagnostic inference are used in the BN to identify:
  (i) Inconsequential hazards and dependencies
  (ii) Critical ranges of hazards and damage states

LEVEL I:

- Preliminary estimate of adverse end event probability

LEVEL II:

- Best estimate of adverse end event probability, using a more efficient BN

NARSIS RISK INTEGRATION – Steps

FEED BACK RESULTS FROM LEVEL I INTO LEVEL II IMPLEMENTATION

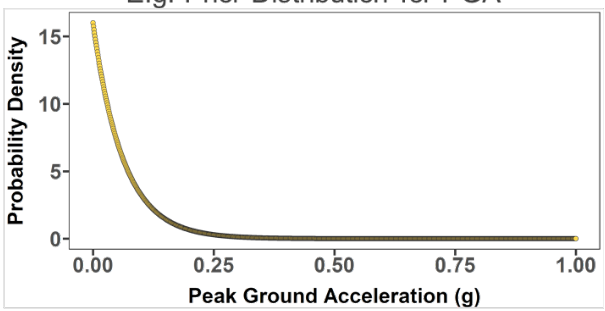
	LEVEL I	LEVEL II
Step 1 **Single and multi-hazard analysis, event sequence definition and fragility modelling** - All relevant hazards and their probability distributions from preliminary hazard analysis are listed - Possible hazard interactions based on Liu et al. (2015) are listed and associated conditional probability distributions are defined (WP1) - Event sequence leading to adverse event of interest is defined (WP1 through 5) - Damage and failure states for SSC are defined - Fragility models are defined for all SSCs for each hazard, including vector-based fragility models (WP2)	- All relevant hazards, IMs and dependencies - Possible to use regional hazard data and generic fragility models	Based on Level I results of sensitivity analysis and diagnostic inference in BN: - eliminate inconsequential hazards, IMs and dependencies - Update hazard and fragility models (if possible and necessary, for e.g. site specific analyses)
Step 2 **Screening hazard probabilities using fragilities models** - Each hazard is assessed against fragility model of every SSC to determine lower threshold magnitude of hazard that initiates damage - Filtered hazard probability distributions are defined	- All relevant hazards and IMs - Possible to use regional hazard data and generic fragility models	- Shorter list of hazards and IMs - Updated hazard and fragility models (if available)
Step 3 **Bayesian network definition** - List of random variables (nodes) – hazards, damage states, and adverse event(s) of interest at the NPP - Directional dependence (arcs) between nodes based on hazard interactions, accident event sequence and expert judgement - Marginal and conditional probability distributions based on filtered hazard information, fragility models, accident event sequence and expert judgement	- All variables (nodes) – hazards and IMs - All dependencies (arcs) between hazards and IMs - Possible to use non-site-specific data to define conditional probabilities	- Shorter list of variables - Lower no. of dependencies - Updated probability distributions (if available)
PREDICTIVE INFERENCE		
Step 4 **Calculating probabilities of damage states and adverse end event** - Conditional probability distributions (based on fragility models) in the BN are used to calculate: (i) Probability of occurrence of damage states of SSCs (ii) Probability of occurrence of adverse end event	- Possible to use generic fragility models to define conditional probabilities	- Updated probability distributions (if available)
Step 5 **Evaluating causal importance and likelihood** - Sensitivity analyses and diagnostic inference are used in the BN to identify: (i) Inconsequential hazards and dependencies (ii) Critical ranges of hazards and damage states	- Preliminary estimate of adverse end event probability	- Best estimate of adverse end event probability, using a more efficient BN

BNs in NPP Risk

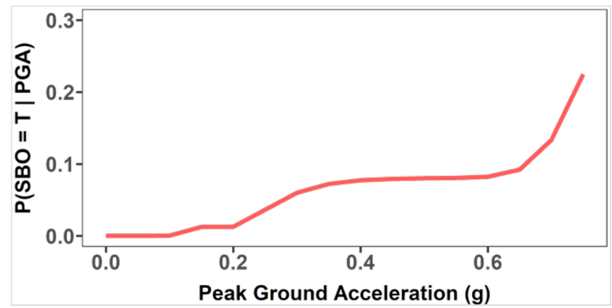
➢ Toy BN - Inference

Predictive Inference – e.g. P(SBO = T) given earthquake PGA

E.g. Prior Distribution for PGA



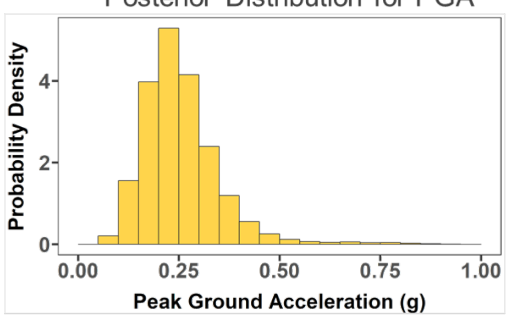
Posterior Distribution for SBO



Diagnostic Inference

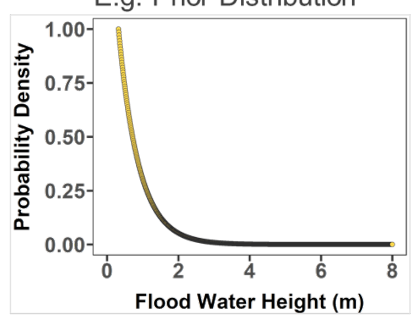
<u>Earthquake PGA given SBO = T</u>

Posterior Distribution for PGA

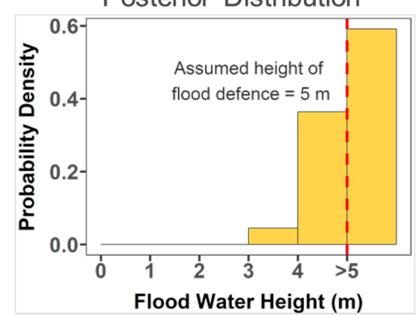


<u>Flood water level, given SBO = T, PGA = 0.05g</u>

E.g. Prior Distribution

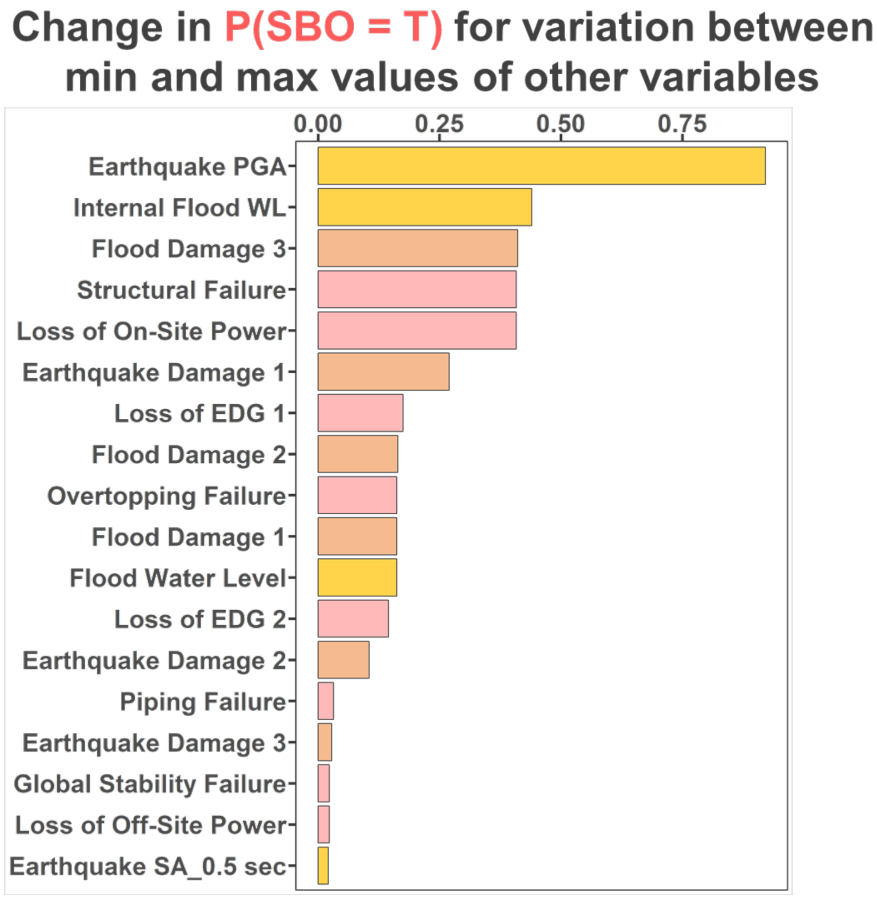


Posterior Distribution



BNs in NPP Risk

➢ Toy BN – Sensitivity Analysis



Summary - BNs for NPP Risk

- Some advantages of BN over conventional methods – e.g. Fault Trees:
- account for dependencies between events
- allow for bi-directional inference: causal and diagnostic
- Allow for discrete or continuous distributions to model random variables
  - The effect of discretization of continuous variables on the risk estimate can be easily studied
- Quantify uncertainty and track its propagation