

A Hybrid Causal Logic Framework for Multi-Hazard Probabilistic Risk Assessment of Nuclear Power Plants

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Outline

Motivation & Need

- 1** Fukushima Daiichi
- 2** Conventional PRA limits
- 3** Multi-hazard methods gap

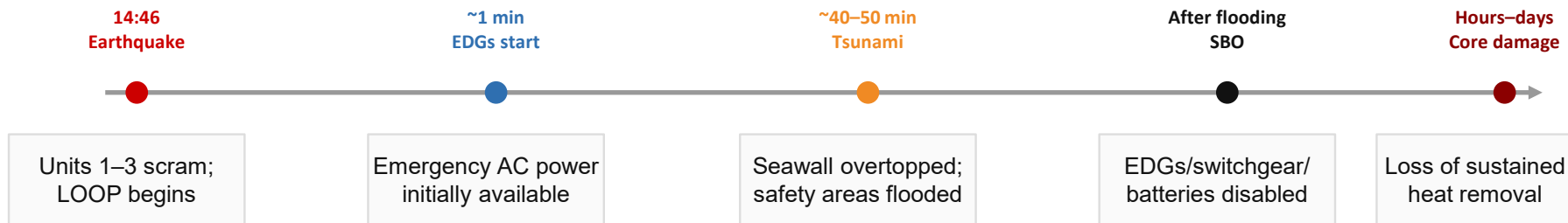
HCL Framework

- 4** HCL concept
- 5** HCL algorithm
- 6** MAAT architecture
- 7** BN dependency model

Case Study & Findings

- 8** PRA and BN case study
- 9** Results
- 10** Limitations and conclusions

Fukushima Daiichi Motivates Multi-Hazard PRA



Limits of Conventional PRA

■ Hazard Level

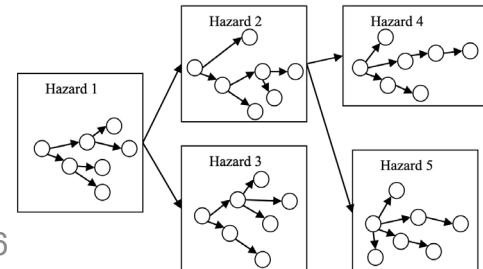
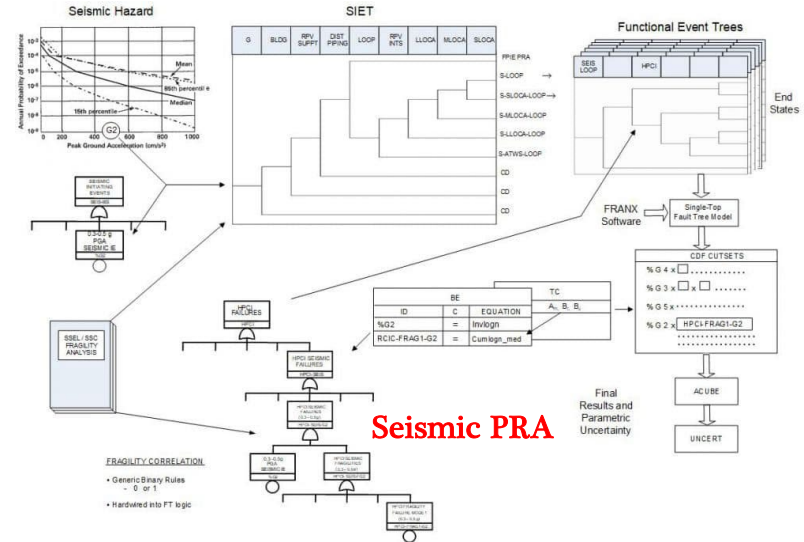
- External hazards evaluated separately (seismic PRA, fire PRA, flooding PRA, etc.).
- Total plant risk from external hazards = sum of the individual hazard contributions.

■ Event Level

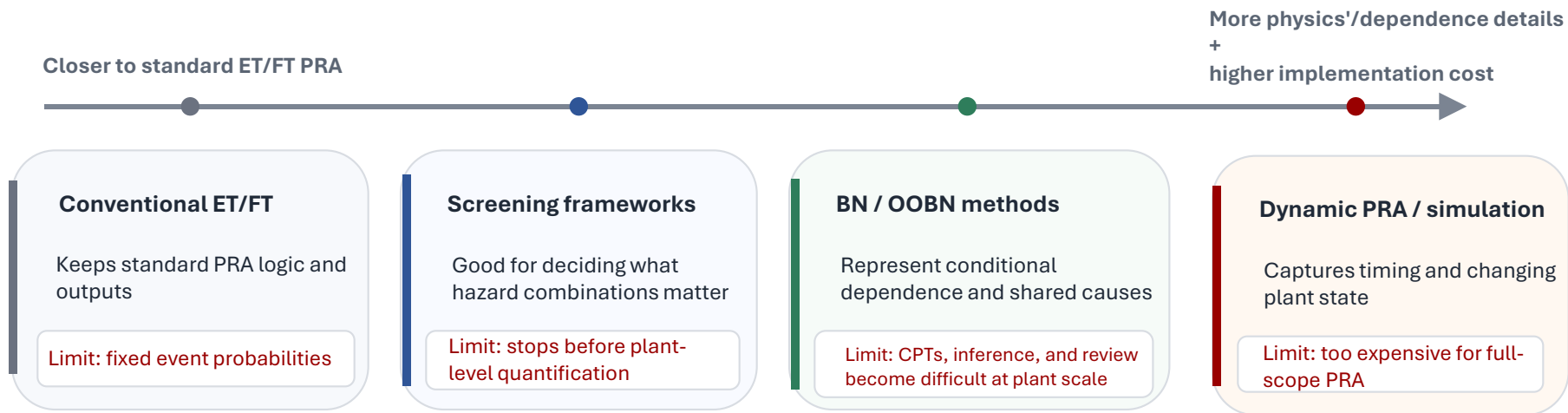
- Failure probabilities : statistically independent
- Limited ability to update events.
- Joint and cascading hazards affect systems differently than a single hazard.

- Ignoring hazard interactions underestimates the risk and overlooks potential vulnerabilities.

Single hazard PRAs work well when independence holds.



Existing Multi-Hazard PRA Methods



Gap: no existing method gives both plant-scale ET/FT PRA and explicit conditioning on the hazard-dependent events that matter.

What is HCL?

Hybrid Causal Logic (HCL) preserves ET/FT logic, compiles it to a BDD, and queries a small BN only for hazard-dependent events.

1 PRA model remains the logic foundation

- Event trees define accident sequences.
- Fault trees define system failures.

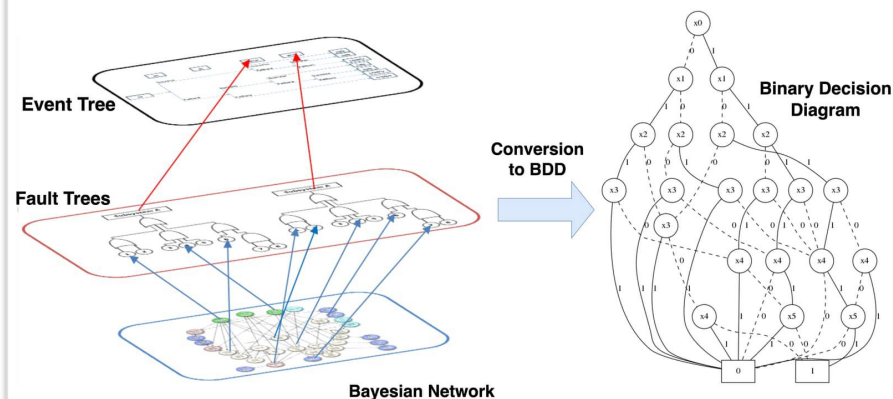
2 ET/FT logic is compiled to a BDD

- BDD traversal evaluates Boolean logic exactly.
- Path evidence is accumulated during traversal for BN linked events.

3 BN queried at intersectional events

- Small BN supplies $P(X \mid \text{path evidence})$ for intersectional events.

Small BN layer: hazard state $\rightarrow$ damage | access | recovery | human action



Standard PRA outputs: CDF, MCS, importance, sensitivity, and UQ.

The HCL Algorithm

Path-Dependent BDD Evaluation

Modified Shannon Decomposition:

Point Mode

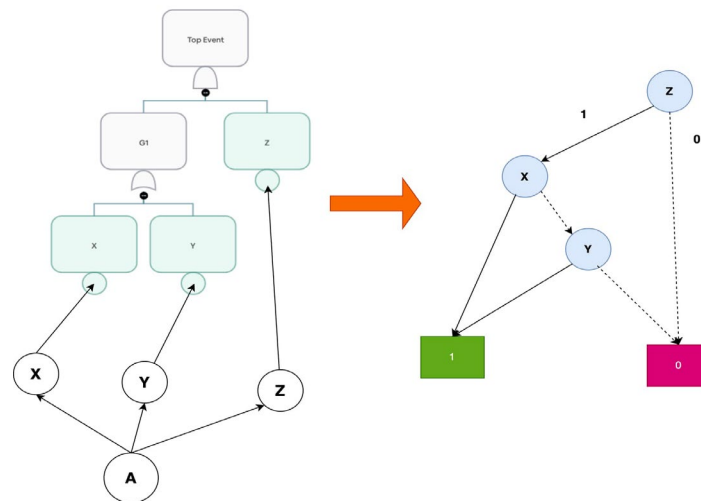
$$q(\alpha, L) = P(x | L) \cdot q(\alpha_1, L \cup x) + [1 - P(x | L)] \cdot q(\alpha_0, L \cup \bar{x})$$

UQ Mode

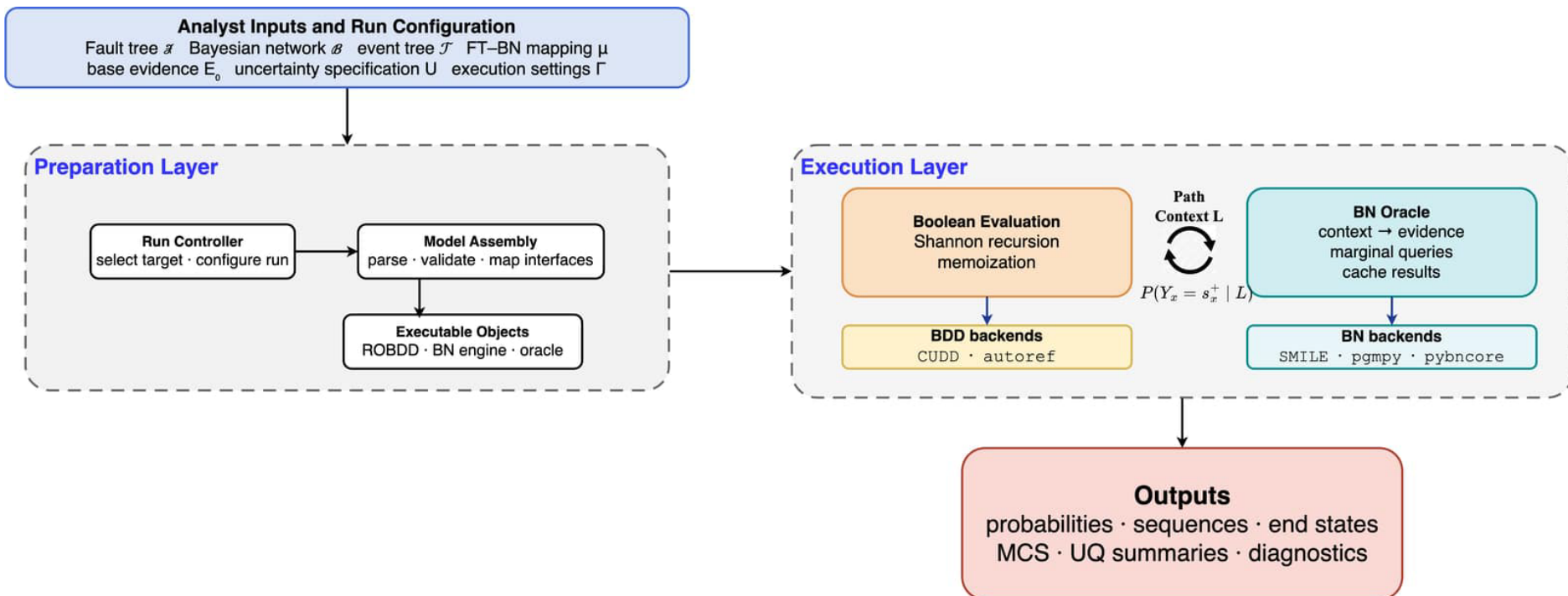
$$q(\alpha, L) = P(x | L) \odot q(\alpha_1, L \cup x) + (1 - P(x | L)) \odot q(\alpha_0, L \cup \bar{x})$$

- $q(\alpha, L)$: probability that the sub-BDD rooted at α evaluates to 1 given evidence L .
- α_1, α_0 : successors on the 1-branch and 0-branch.
- $L \cup x, L \cup \bar{x}$: evidence after taking the 1- or 0-branch.
- If x is **not** intersectional: $P(x | L) = P(x)$

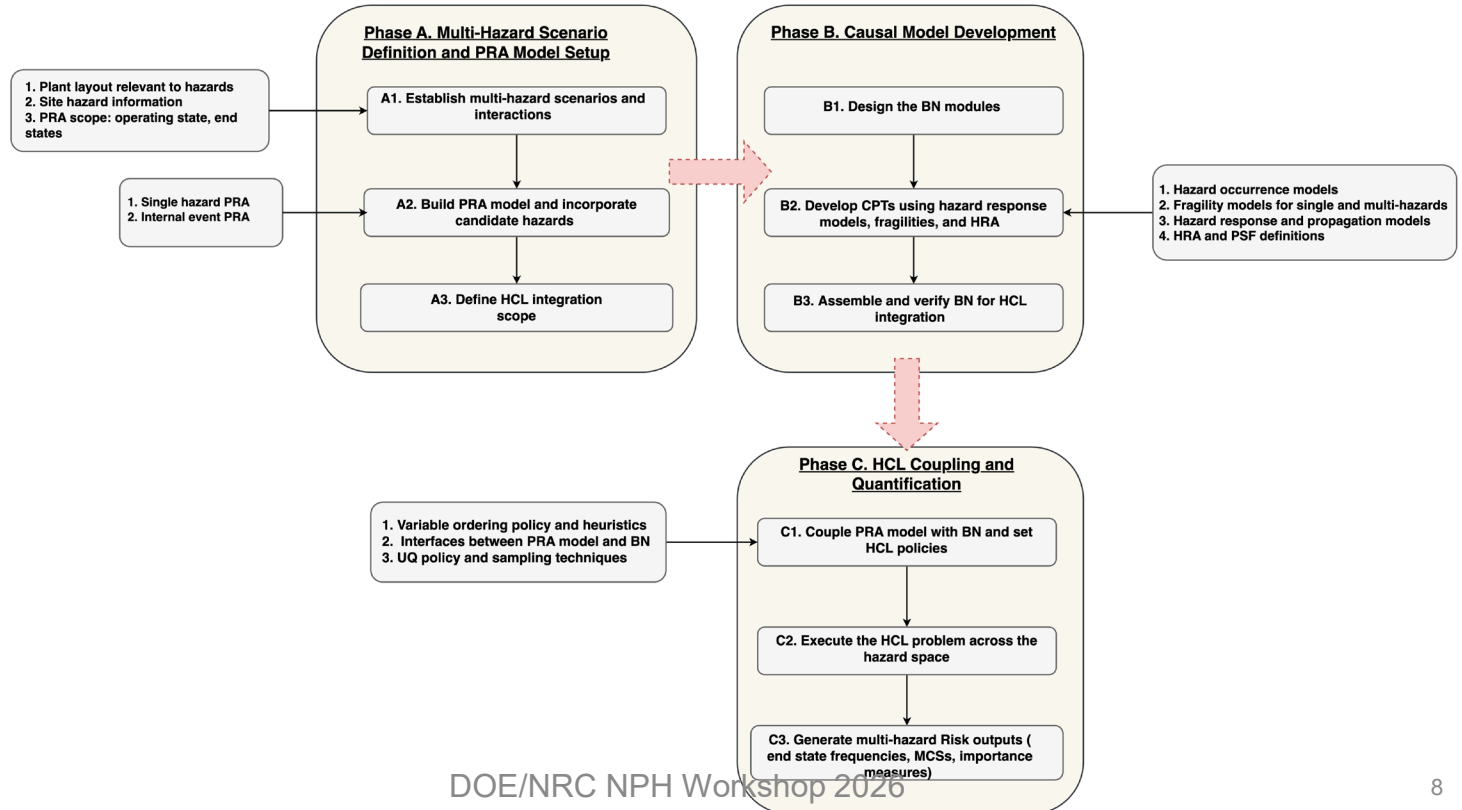
HCL problem converted to a BDD



MAAT Platform Architecture



Applying the HCL Framework: Three-Phase Workflow



BN Framework for Multi-Hazard Dependency

BN Layers

1 Hazard fields and interactions

Hazard occurrence/intensity; secondary hazards and interactions

2 Mitigation and human action

Detection, suppression, isolation, and performance-influencing factors.

3 Exposure

Component-level hazard intensity at the target location.

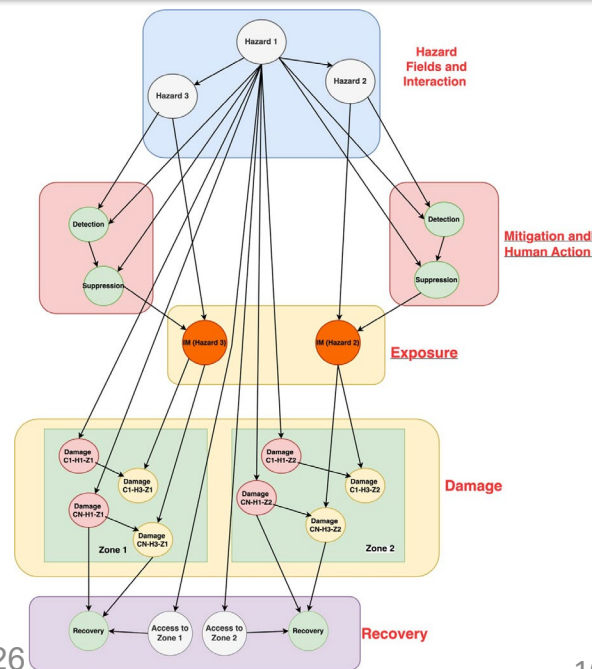
4 Damage states

Fragility-based failure modes; compound or sequential damage.

5 Recovery

Restoration conditioned on damage, hazard conditions, and access.

Five-layer dependency model



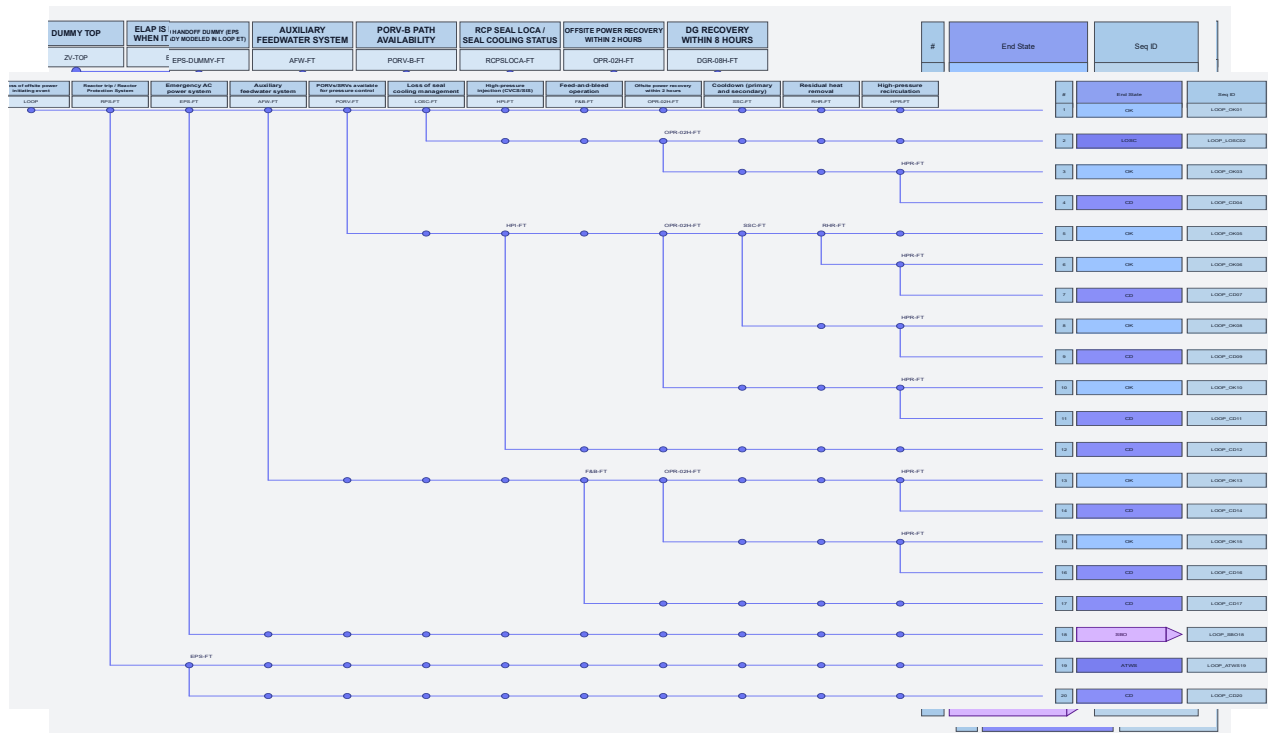
Case Study PRA Model : LOOP → SBO → FLEX

PRA Model Event Trees

- **LOOP ET:** LOOP initiating event, reactor trip, emergency AC power, AFW, pressure control, and offsite power recovery.
- **SBO ET:** Emergency power failure, offsite power recovery, and diesel generator recovery.
- **FLEX ET:** ELAP declaration, FLEX diesel and pump connection, and AC power recovery

Why these Sequences?

- **Fukushima Sequence:** LOOP event escalated into a long-term SBO
- **FLEX Benefit Test:** To test how hazards impact FLEX (a post-Fukushima mitigation strategy)

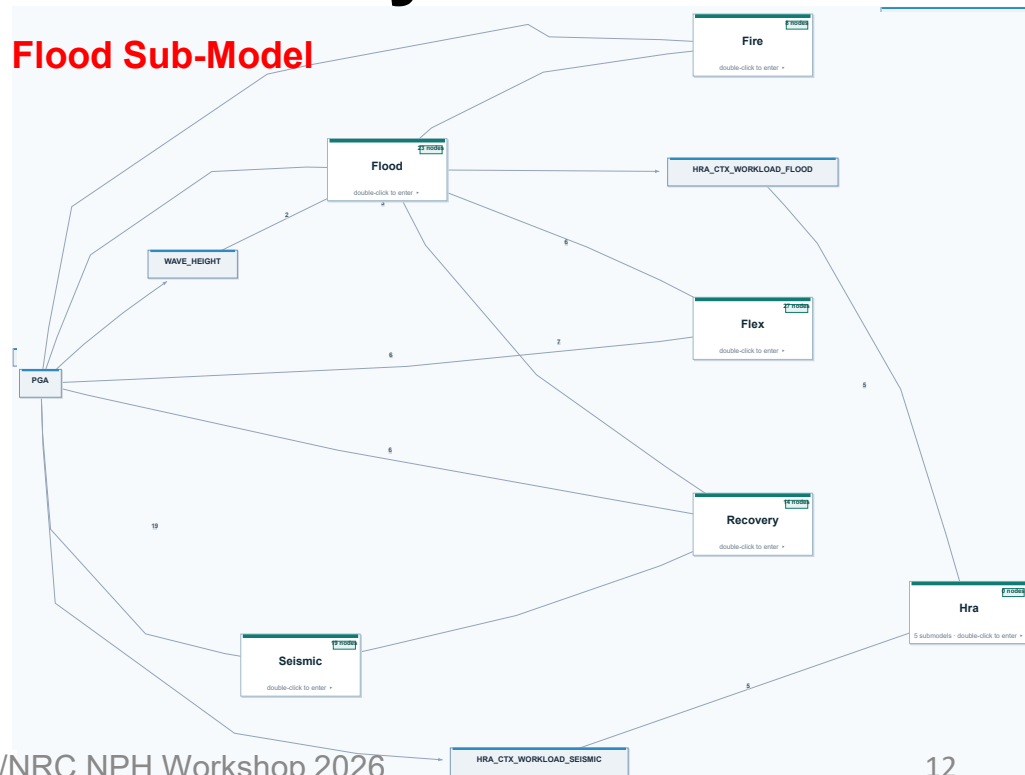


Case Study PRA Model: Bayesian Network

Bayesian Network Sub-Models

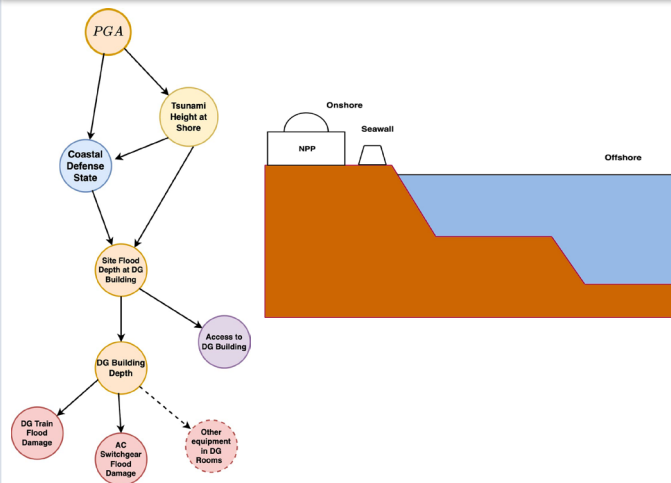
- **Seismic:** Defines seismic hazard-induced damage to SSCs and site conditions.
- **Flood :** Represents flood propagation logic from site boundary into plant areas and building internals, including component damage and access degradation.
- **Fire :** Captures fire-induced damage in 4.16 kV Switchgear Room A, including switchgear control/protection cables and A-train 4.16 kV power cables
- **Recovery:** Captures offsite-power and diesel generator recovery, access to their locations and the impact of hazards on recovery actions.
- **FLEX:** Represents the availability and deployment of portable electrical, steam generator and makeup support under conditions of combined hazards.
- **HRA:** Conditions selected operator/support actions on scenario context, access, timing, workload, signal quality, and other PIFs.

Flood Sub-Model

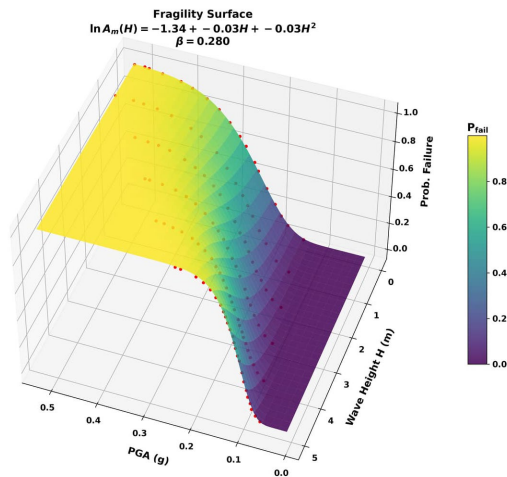


External Flooding & Coastal Defense Fragility

External-flood cascade



Multi-hazard dike fragility



Coastal defense state depends on both PGA and tsunami wave height.

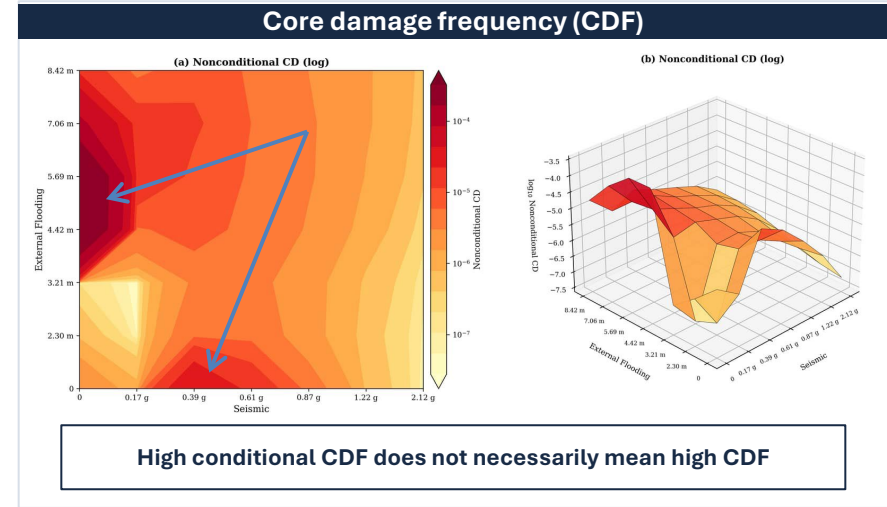
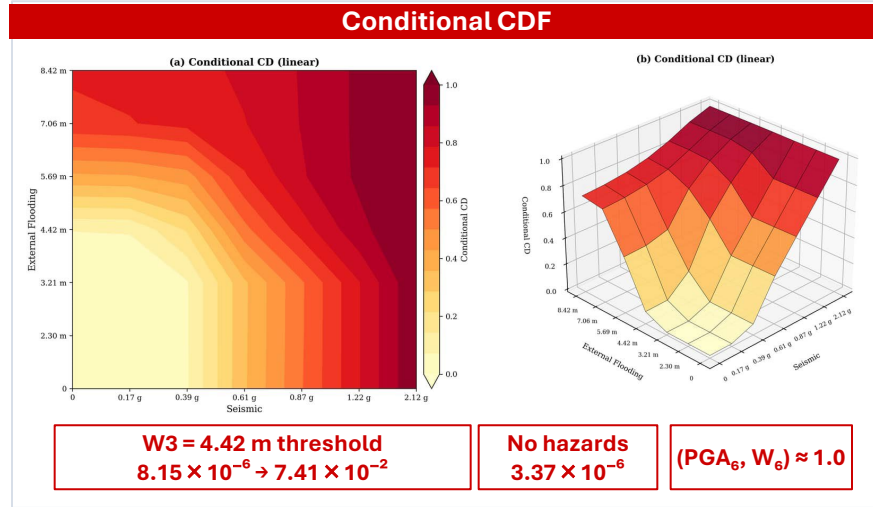
Dike failure modes

Intact / protected
barrier remains effective.

Overtopped
Water level exceeds the defense crest and flows over the barrier.

Breached
A sustained opening forms through the defense. Failure mechanisms include piping, random failure, and combined hazard failure.

Core Damage Across the Hazard Matrix

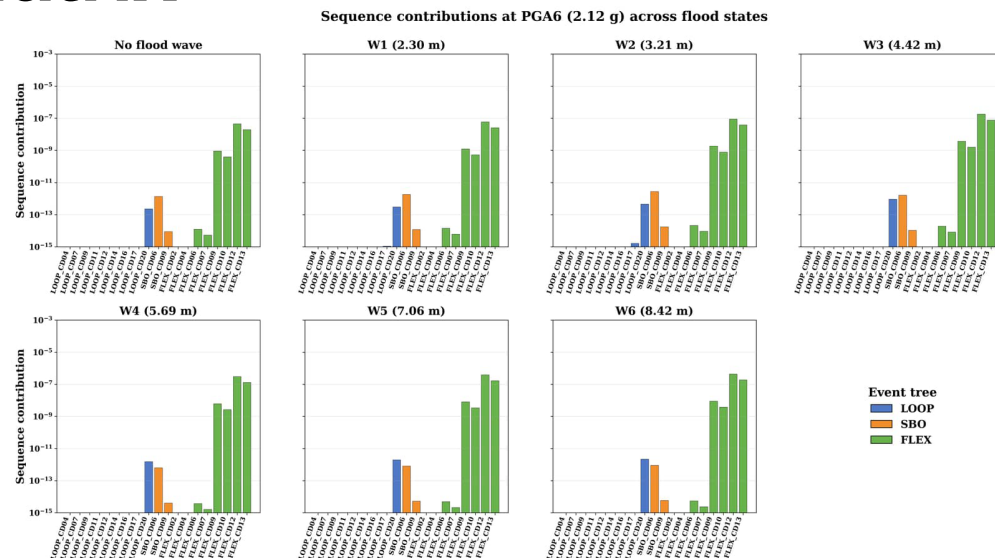
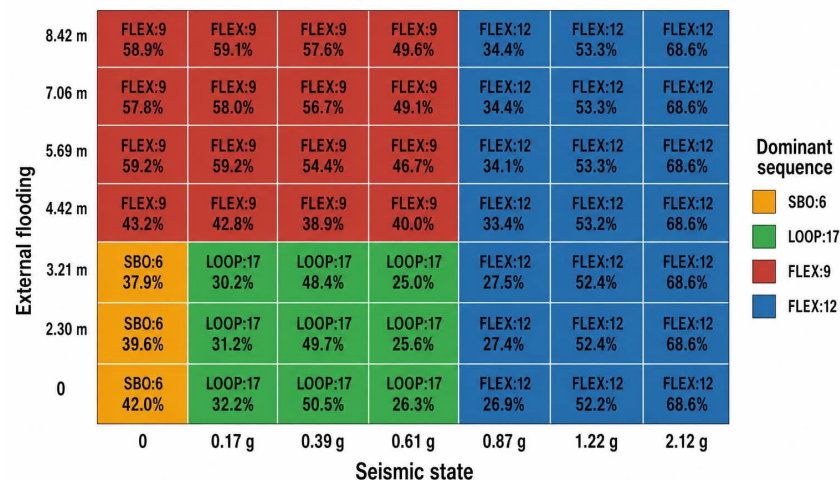


■ **Conditional CD rises sharply at W3 = 4.42 m due to mostly coastal-defense overtopping.**

■ **CDF shifts attention to W3, W4 and low-to-moderate seismic cells.**

■ **The highest-intensity cells are severe, but their hazard frequencies are small.**

Dominant Accident Regimes in the Hazard Matrix



■ Near baseline: no single family dominates; SBO, LOOP, and FLEX all contribute.

■ Around W3 = 4.42 m, flood-induced failures pushes the model toward FLEX.

■ At high seismic intensities, contribution is increasingly FLEX-family dominated.

Coastal Defense Upgrade: CDF Reduction

Total CDF

$9.71 \times 10^{-4}/\text{yr} \rightarrow 1.76 \times 10^{-4}/\text{yr}$

82% reduction

Upgrade assumptions

Crest: 2.0 $\rightarrow$ 7.5 m

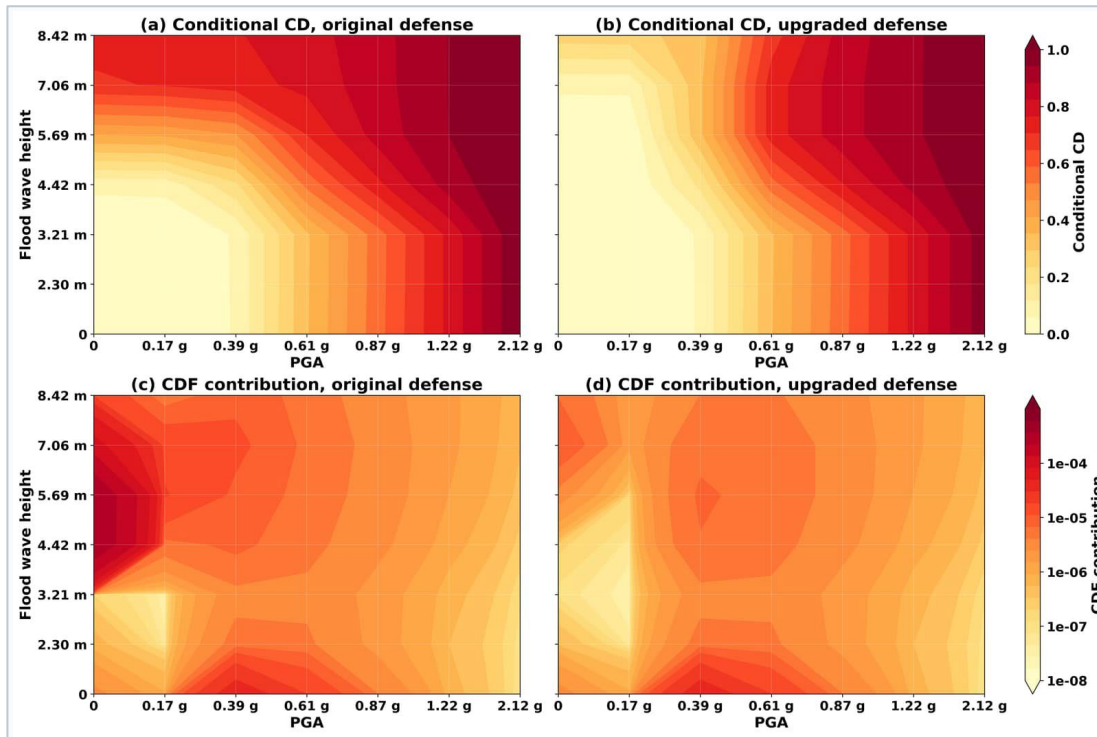
Random breach: $5 \times 10^{-4} \rightarrow 1 \times 10^{-4}$

Piping median: 3.5 $\rightarrow$ 7.0 m

Interpretation

- The W3-W5 flood band is largely suppressed.
- Flood-only cells no longer drive near-certain core damage.
- Remaining contribution shifts to $\text{PGA}_2/\text{PGA}_3$.

The upgrade reduces total CDF and changes where the remaining risk comes from.



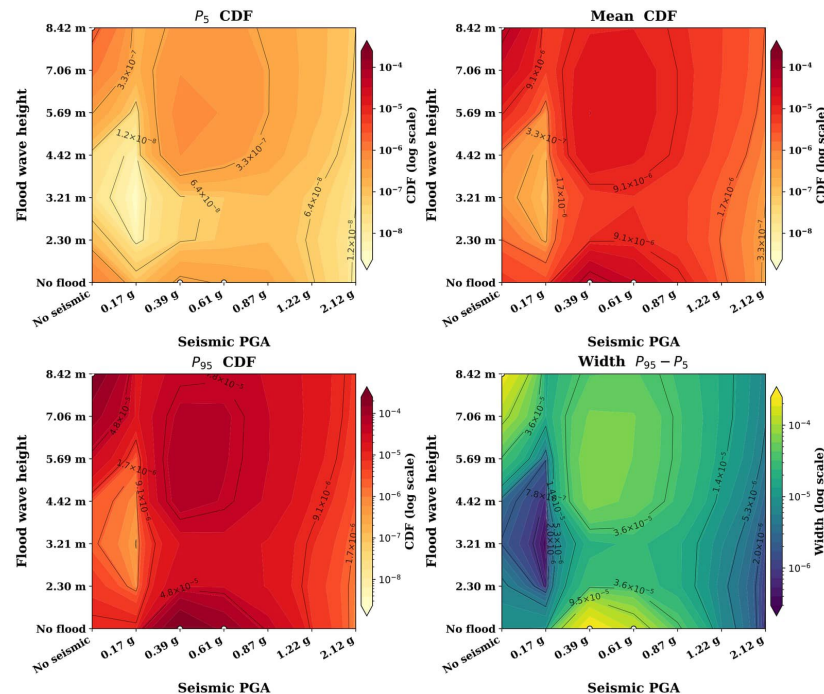
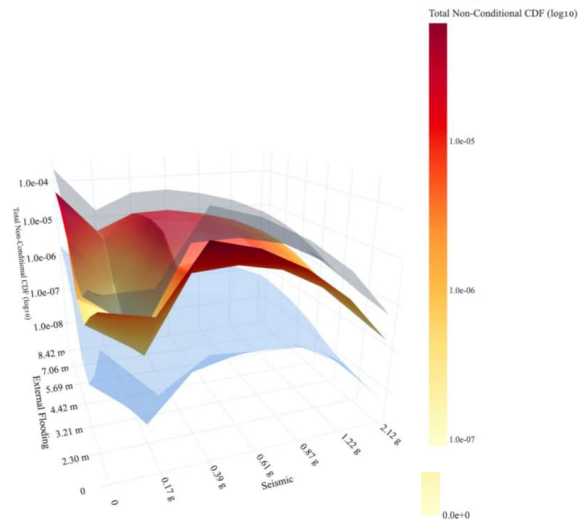
Uncertainty Propagation Across the Hazard Matrix

UQ Scope

- UQ applied only to the No-FLEX case with upgraded coastal defense.
- Adaptive sampling approach was followed (cell-wise samples range from 8,000 to 20,000 samples)

Observed UQ pattern

- Largest conditional width: 0.87g, no flood; mean CD = 0.571; Width = 0.672.
- Largest CDF width: 0.39g, no flood; Width = 2.48×10^{-4} /yr.
- Top 10 cells account for 64.1% of summed cellwise CDF width.

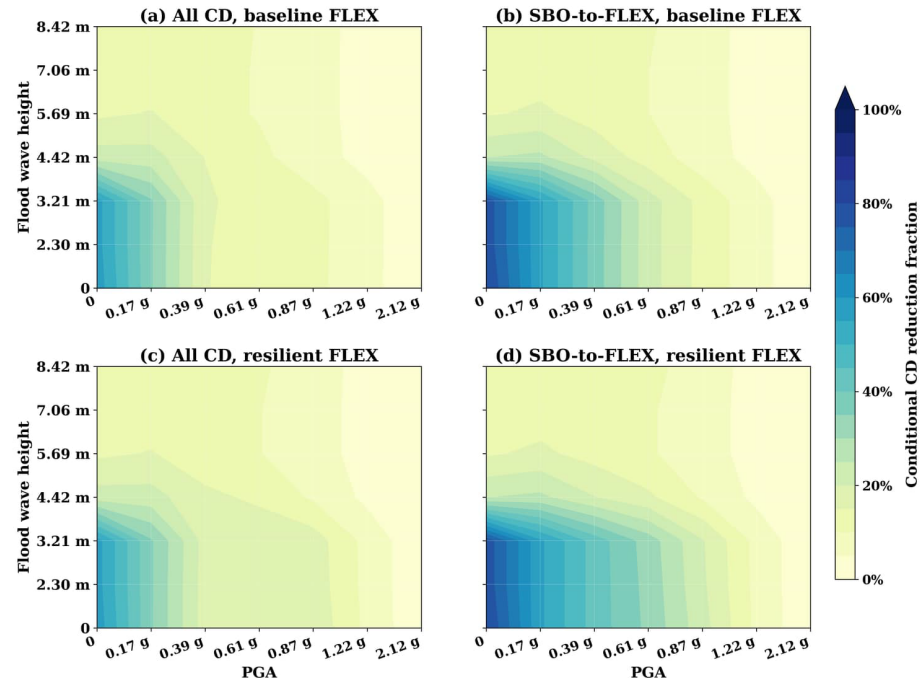


FLEX Credit After Coastal-Defense Upgrade

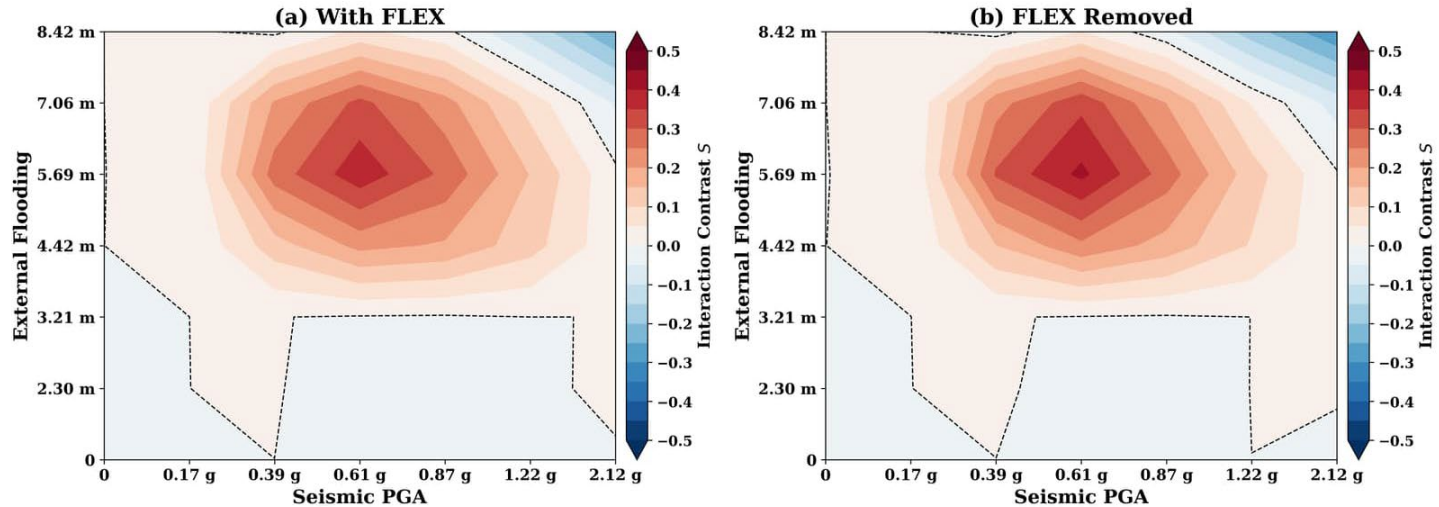
Observed results

- FLEX credit is largest in low-seismic/low flood cells.
- The SBO→FLEX case shows larger credit because it removes paths that bypass FLEX.
- At high PGA and wave heights, FLEX deployment and support functions are vulnerable, so the relative credit falls significantly.

Conditional CD reduction when FLEX is credited relative to the no-FLEX case.



Multi-Hazard Interaction



Interaction contrast (conditional CD)

$$S(PGA, W) = P(CD|PGA, W) - [P(CD|PGA, W_0) + P(CD|PGA_0, W)]$$

S = combined hazard response – additive single hazards

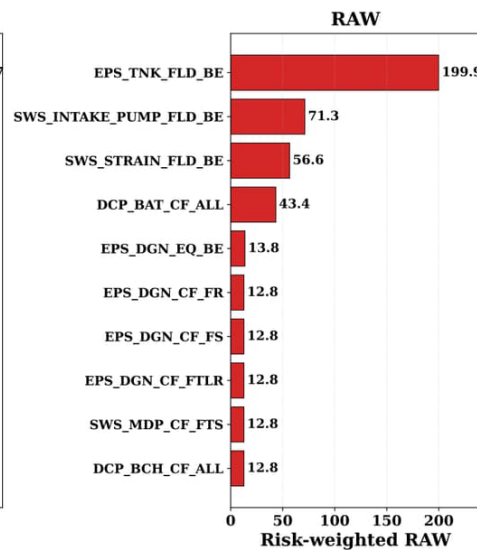
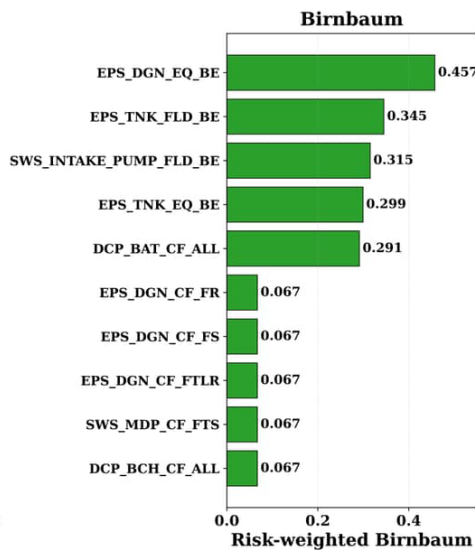
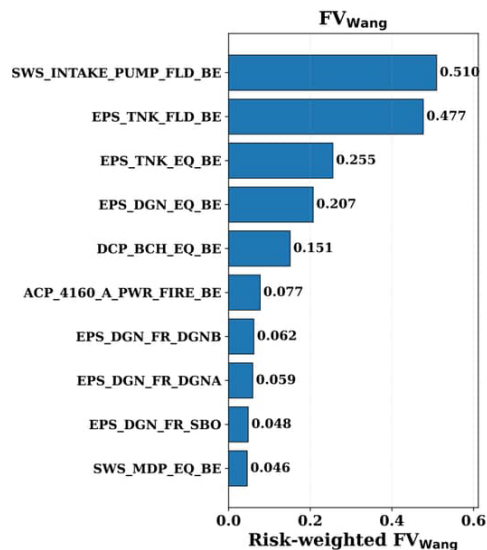
PGA_0 = no seismic; W_0 = no flood

Dashed contour: $S = 0$

S interpretation

- $S = 0$: additive single-hazard response
- $S > 0$: positive interaction
- $S < 0$: probability saturation

Importance Measures Analysis



SWS_INTAKE_PUMP_FLD_BE

Service-water intake pump flood failure

EPS_TNK_FLD_BE

Emergency power system tank/day-tank flood failure

EPS_DGN_EQ_BE

Emergency diesel generator seismic failure

DCP_BAT_CF_ALL

DC power/battery charger CCF

SWS_STRAIN_FLD_BE

Service-water strainer flood failure

DCP_BCH_CF_ALL

DC power/battery charger CCF

Limitations: Data and Modeling

Limited multi-hazard data

Joint hazard frequencies and multi-hazard SSC fragilities are limited, especially for nuclear plant components.

HRA under combined hazards

HRA data for combined hazards, degraded access, and disrupted work conditions are unavailable.

Seismic failure correlation

The case study assumes independent seismic SSC failures. Correlated failure among co-located or similar components was not modeled.

Next step: Similar components can share fragility information

Limited treatment of time dependence

The BN is mostly static. Recovery timing, interrupted field actions, and evolving site conditions are represented through discrete states but it is not a dynamic progression.

Limitations: Scaling

Intersectional node context growth

More BN–PRA interfaces create more evidence contexts and BN queries during BDD traversal.

Next step: selective mapping; context-reduction policies

BDD/order tradeoff

Two-block ordering avoid context memory explosion, but it may prevent us from achieving a good variable order.

Next step: improved ordering and block-partitioning heuristics

Hazard-space sweep cost

More hazard axes and UQ samples multiply runtime; a 2D grid is manageable, but higher-dimensional hazard matrix would be computationally intractable

Next step: Add more hazards ; parallel computing; Coarser hazard grids

Discrete nodes and exact BN inference

The current implementation uses discrete BN nodes and exact inference, so continuous variables must be binned and very large BNs may become expensive.

Next step: hybrid nodes; approximate inference options

What HCL Enables

1. PRA integration

- Keeps ET/FT logic explicit and traceable.
- Uses BN queries to represent hazard-conditioned dependencies without rebuilding the PRA as a full BN.
- Preserves PRA's conventional outputs for interpretation and decision-making.

2. Multi-hazard interaction

- Captures joint, induced, and cascading dependencies within a unified framework.
- Separates additive hazard effects from true multi-hazard interaction.
- Shows how accident progression changes under different hazard conditions.

3. Decision support

- Maps where vulnerabilities and dominant contributors shift across the hazard space.
- Evaluates the benefit and limits of mitigation measures such as recovery actions and FLEX strategies.
- Supports risk-informed prioritization for modeling, design, and emergency planning.

Questions?



BACKUP SLIDES

Outlines

Motivation and research objectives

- 1** Motivation
- 2** Problem statement
- 3** Research objectives

PRA Methods & HCL

- 4** Approach overview
- 5** PRA and multi-hazard methods
- 6** Hybrid Causal Logic
- 7** Integrated multi-hazard BN

Case Study & closeout

- 8** Case study and results
- 9** Limitations
- 10** Future work

Motivation and Research Objectives

Motivation

1

Fukushima Daiichi

2

Conventional PRA limits

3

Multi-hazard PRA guidance

What this work does

4

Problem statement

5

Research objective

6

Proposed approach

Sections: motivation → problem statement → research objective → proposed approach

National and International Push for Multi-Hazard PRA

IAEA / OECD-NEA

Post-Fukushima guidance calls for explicit treatment of joint, correlated, and induced hazards in external-hazard PSA.

ASME/ANS PRA standards

Standards require identification and screening of multi-hazard initiating events, including concurrent and induced scenarios.

Primary Objectives

Modeling Joint hazard occurrence

Mandating the Assessment of Secondary and Cascading Hazards

Evaluating Synergistic and Cumulative Impacts

Preventing Simultaneous Defense-in-Depth Failures

Accounting for Multi-Unit Vulnerabilities

OPEN GAP

No widely adopted method links multi-hazard dependencies to ET/FT logic while preserving standard PRA outputs.

Problem Statement

Conventional ET/FT PRA

- Preserves sequence and system logic
- Scales well for large plant models
- Treats most basic events with fixed probabilities
- Struggles with multi-hazard events

Full BN Conversion

- Captures conditional dependence directly
- Turns much of the PRA into nodes and CPTs
- Becomes hard to build, solve, and review at plant scale
- MCSs is not native BN outputs

Needed Capability

- Keep ET/FT as the PRA logic model
- Use BN conditioning only where the independence assumption breaks
- Let shared hazard states update damage, access, recovery, and HRA events
- Keep PRA outputs from the logic layer: CDF, MCSs, importance, sensitivity

Shared hazard state

→ component damage | access limits | recovery delay | human action

Core problem: account for multi-hazard dependencies without abandoning the ET/FT structure that makes PRA scalable, reviewable, and interpretable.

Research Objectives

1

HCL-Based Integration for Multi-Hazard PRA

- Apply HCL to multi-hazard ET/FT–BN coupling through intersectional events
- Implement BDD traversal with path evidence for hazard-conditioned events

2

MAAT Implementation & Verification

- Implement the HCL solver different layers: BN oracle, BDD engine, and UQ sampling workflow
- Verify the implementation against analytical cases, unified-BN references, and PRA benchmarks

3

Multi-Hazard BN Design

- Build a layered BN structure for hazard state, exposure, damage, access, and recovery
- Use the BN to represent shared site conditions, induced hazards, and degraded response

4

Case Study & Risk Insights

- Apply the method to a seismic–flood–fire LOOP/SBO/FLEX case study
- Quantify CDF, MCSs, importance, uncertainty, sensitivity, and mitigation effects across the 7×7 hazard matrix

PRA Fundamentals & Methods used in HCL

PRA fundamentals

- 1** Risk triplet: scenarios, likelihoods, consequences
- 2** Event trees define accident sequences and end states
- 3** Fault trees reduce failures to basic events and cut sets

Methods used by HCL

- 4** BDDs quantify Boolean logic with ordered variables
- 5** BNs represent hazard-conditioned dependencies
- 6** HCL keeps ET/FT logic while conditioning key probabilities

Sections: risk triplet → event trees → fault trees / MCSs → BDDs → Bayesian networks → HCL requirements

PRA and the Risk Triplet

1

What can go wrong?**Scenarios s_i**

Initiating events, hazard states, and accident paths leading to end states.

2

How likely is it?**Likelihoods L_i**

Frequency and probability of events.

3

What are the consequences?**Consequences x_i**

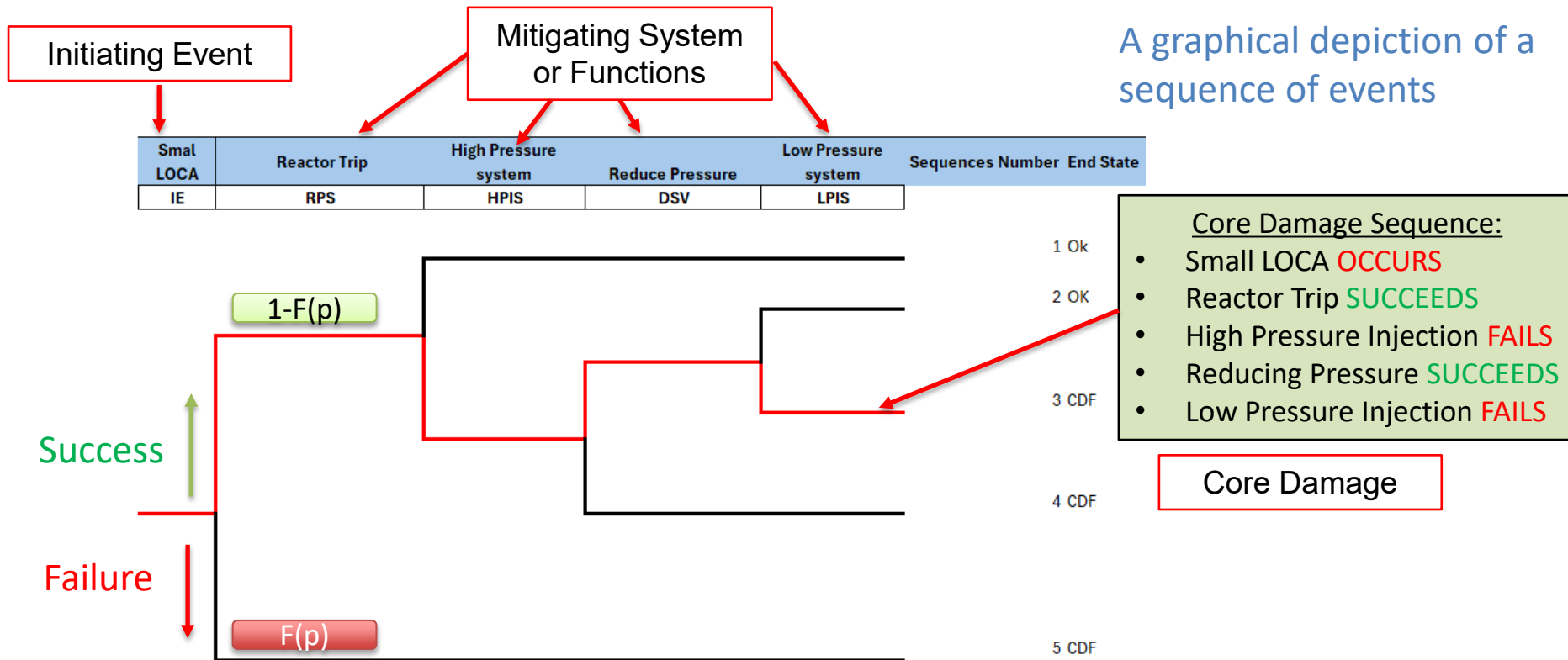
End states such as core damage, release categories, or public consequences.

Risk is represented as

$$R = \{\langle s_i, L_i, x_i \rangle\}_c$$

What is an event tree?

A graphical depiction of a sequence of events



What is a fault tree?

TOP EVENT
(system/function failure
from event tree)

LOW PRESSURE
INJECTION FAILS

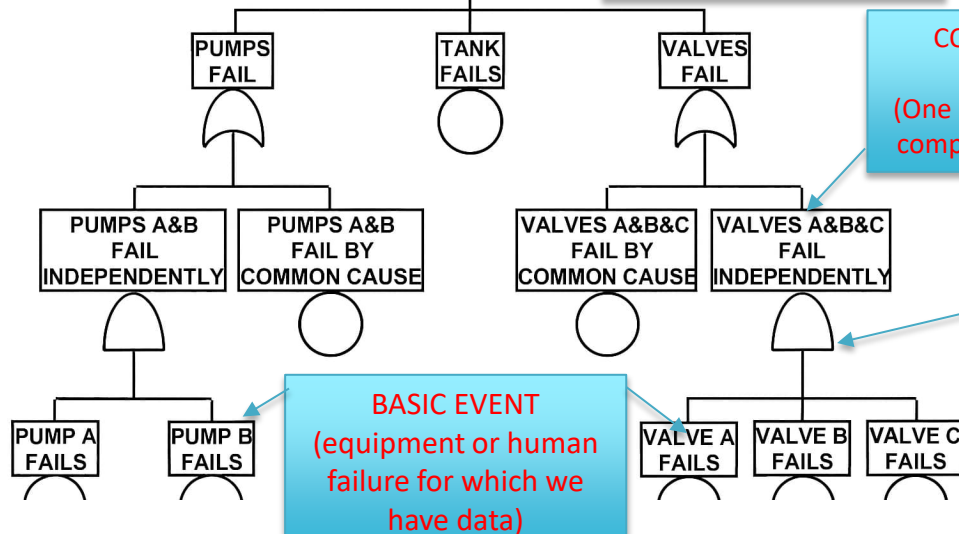
OR GATE
(a failure of any input
causes overall
failure)

SUCCESS CRITERION:

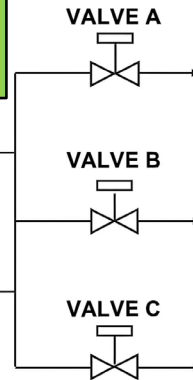
Flow from the tank through 1 of 2
pumps to 1 of 3 injection paths

**COMMON CAUSE
FAILURE**
(One mechanism fails all
components in a group)

AND GATE
(all inputs must fail to
cause overall failure)



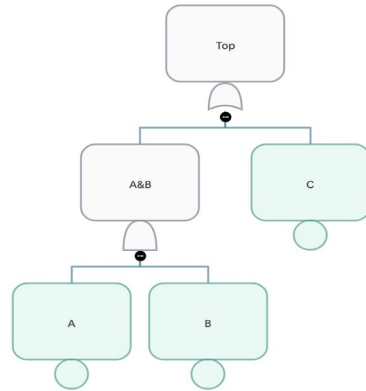
(LPIS)



Minimal Cut Sets

Example: Top = C OR (A AND B)

MCSs: {C} and {A,B}



- MCS is the minimal set of basic events that causes the top event.
- MCSs identify dominant failure combinations and single points of vulnerability.

Exact evaluation

$$P(\text{Top}) = P\left(\bigcup_i \text{MCS}_i\right)$$

Accounts for overlap among cut sets

Rare Event Approx. (REA)

$$P(\text{Top}) \approx \sum_i P(\text{MCS}_i)$$

Fast approximation. Can overestimate when cut sets overlap or probabilities are not rare.

Min-Cut Upper Bound (MCUB)

$$P(\text{Top}) \approx 1 - \prod_i (1 - P(\text{MCS}_i))$$

Common conservative bound for coherent logic with independent basic events. Can be inaccurate at high probabilities.

Binary Decision Diagrams (BDDs)

What is a BDD?

Rooted directed acyclic graph (DAG)
representation of a Boolean function with ordered
variables and 0/1 terminal nodes

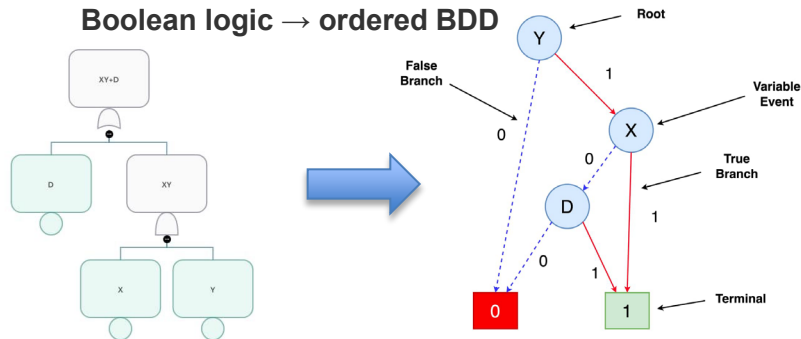
Shannon Decomposition

$$f = xf_{x=1} + \bar{x}f_{x=0}$$

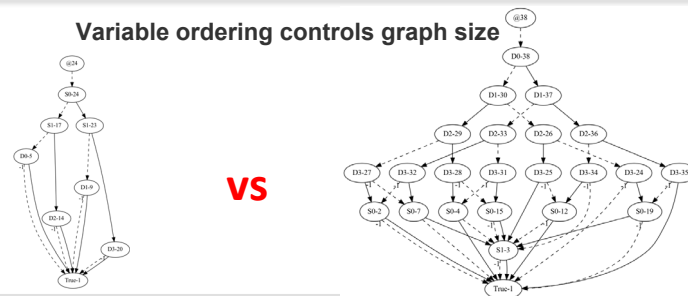
$$P(f) = P(x)P(f_{x=1}) + (1 - P(x))P(f_{x=0})$$

Exact Boolean quantification. In HCL, intersectional events
use BN-conditioned probabilities.

Boolean logic → ordered BDD



Variable ordering controls graph size



VS

Bayesian Networks

What is a Bayesian Network?

A Bayesian Network represents random variables and their conditional dependencies using a directed acyclic graph (DAG). The DAG encodes conditional independence: each node is independent of its non-descendants given its parents.

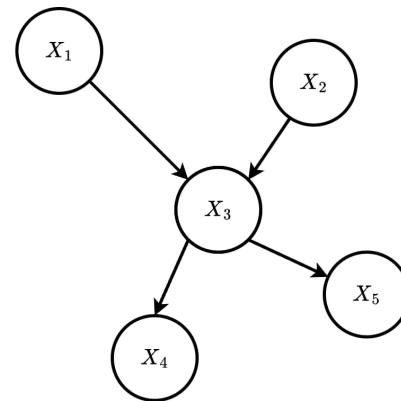
Graph semantics

- Nodes: represent variables (e.g., hazards, component states, human action).
- Edges: represent direct conditional dependencies.

Probability model

Each node is associated with a Conditional Probability Table (CPT). The joint distribution factors into local parent-conditioned terms:

$$P(X_1, X_2, \dots, X_n) = \prod_{i=1}^n P(X_i \mid \text{Parents}(X_i))$$



Requirements for the HCL Approach

1

Keep ET/FT as the accident model

Event trees and fault trees should still define the sequences, systems, and logic.

2

Selective dependency modeling

Apply hazard-conditioned probabilities where hazard state affects failures, access, recovery, or human actions.

3

Avoid converting PRA model to BN

Most basic events are ordinary random failures and do not need dependency modeling.

4

Extract standard PRA outputs

CDF, sequence frequencies, MCSs, importance, sensitivity, and uncertainty results should still come from solving the model

HCL Method & MAAT implementation/Verification

Hybrid Causal Logic method

- 1 Preserve event-tree and fault-tree PRA structure
- 2 Use the BN only at intersectional events
- 3 Evaluate paths with context-aware BDD recursion

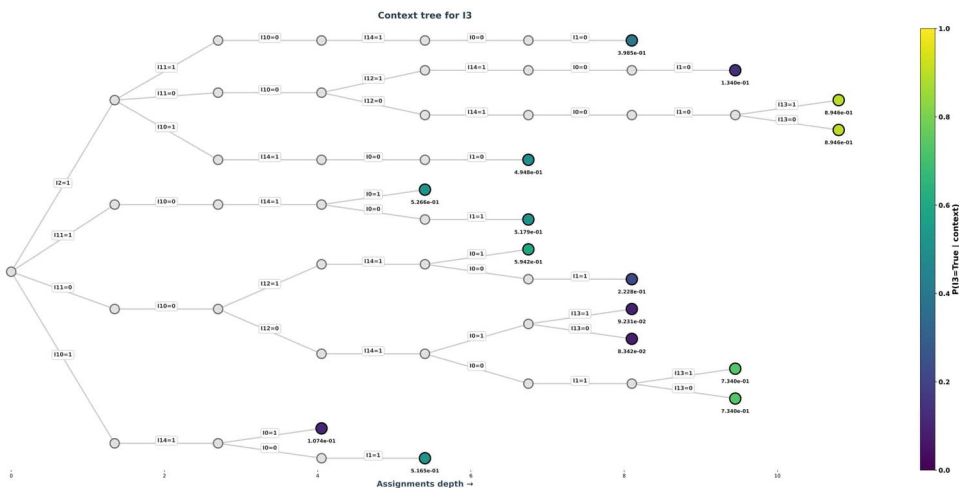
MAAT implementation and verification

- 4 Separate preparation, execution, and outputs
- 5 Reduce BN calls through context and ordering policy
- 6 Carry UQ through tensorized BN inference and verification

Sections: HCL concept → iterative algorithm → MAAT architecture → context reduction / ordering → UQ → verification

Reducing BN Queries

BDD traversal creates many path contexts



The same BDD node may have different probability if reached under different evidence.

Context Management in HCL

1

Keep intersectional events only

FT-only events stay in the BDD solver; they are not sent as BN evidence.

2

Encode the mapped context

Intersectional events are encoded as a (mask, value) evidence key for BN queries.

3

d-separation pruning (optional)

When enabled, remove evidence that the BN graph proves irrelevant to the query.

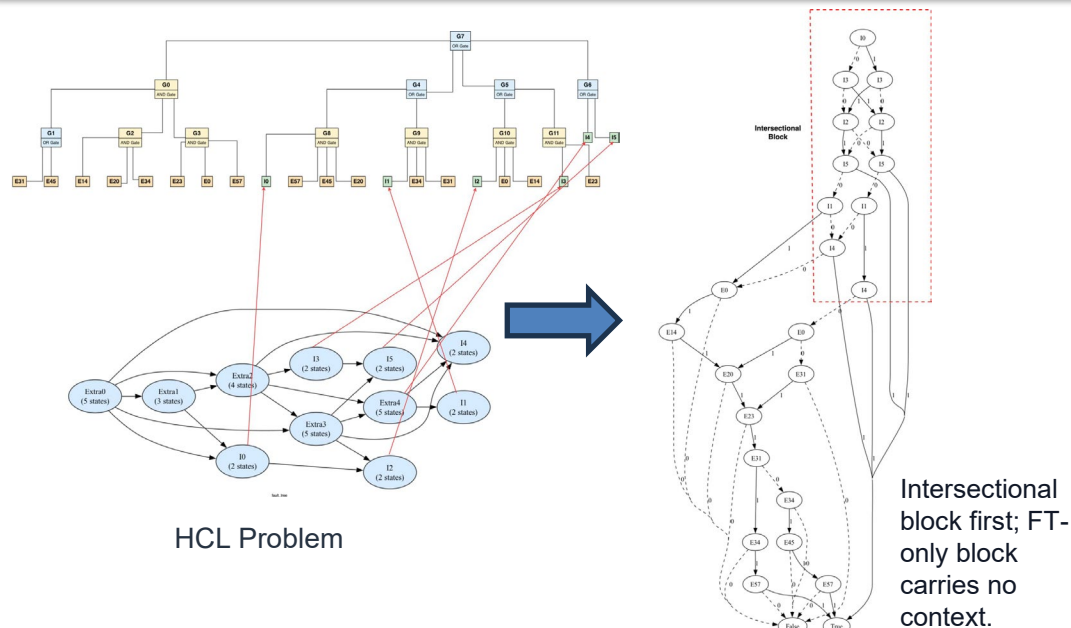
4

Cache and reuse BN results

Repeated mapped/evidence contexts share the same oracle result.

Two-Block Ordering

Two-block ordering Visualization



Why the two-block ordering is used

Issue

- 1
 - Interleaved order can be memory-heavy
 - A compact BDD can scatter intersectional events
 - memo entries then carry both node and BN context.

Solution

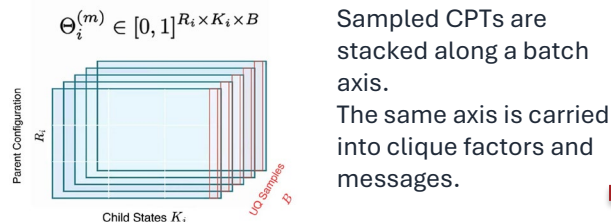
- 2
 - Two-block order localizes context
 - Intersection events are traversed first;
 - FT-only subgraphs create no new BN evidence.

Tradeoff

- 3
 - A forced intersectional block can be a poor ordering that increases BDD size significantly.

Tensorized BN Inference for UQ

1. Add a sample axis



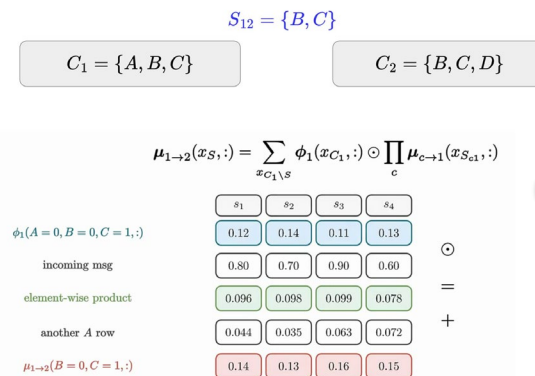
$$\phi_C(x_C, :) = [\phi^{(1)}, \phi^{(2)}, \dots, \phi^{(B)}]$$

State tuple	s_1	s_2	s_3	s_4	...	s_B
$x_C^{(1)}$	$\phi_1^{(1)}$	$\phi_1^{(2)}$	$\phi_1^{(3)}$	$\phi_1^{(4)}$	...	$\phi_1^{(B)}$
$x_C^{(2)}$	$\phi_2^{(1)}$	$\phi_2^{(2)}$	$\phi_2^{(3)}$	$\phi_2^{(4)}$	...	$\phi_2^{(B)}$
$x_C^{(R)}$	$\phi_R^{(1)}$	$\phi_R^{(2)}$	$\phi_R^{(3)}$	$\phi_R^{(4)}$	...	$\phi_R^{(B)}$

Continuous SIMD Lanes

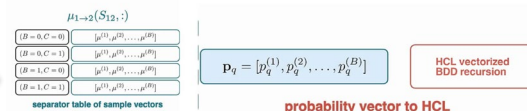
CPT tensor $\rightarrow$ factor/message tensors

2. Pass vector-valued messages



Shafer-Shenoy message passing is unchanged. Each factor entry is now a vector over UQ samples.

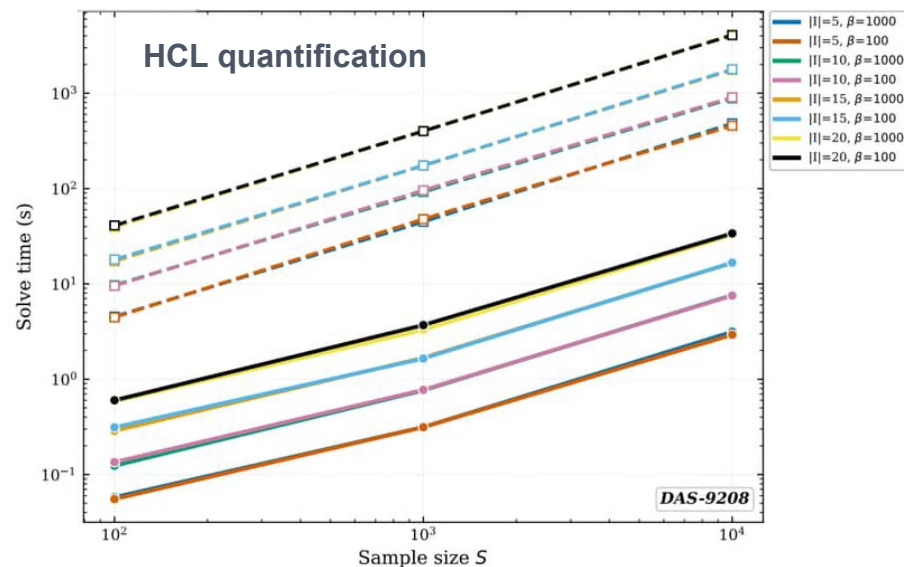
3. Return probability vectors to HCL



The BN oracle returns a sample-aligned probability vector directly to the HCL BDD solver.

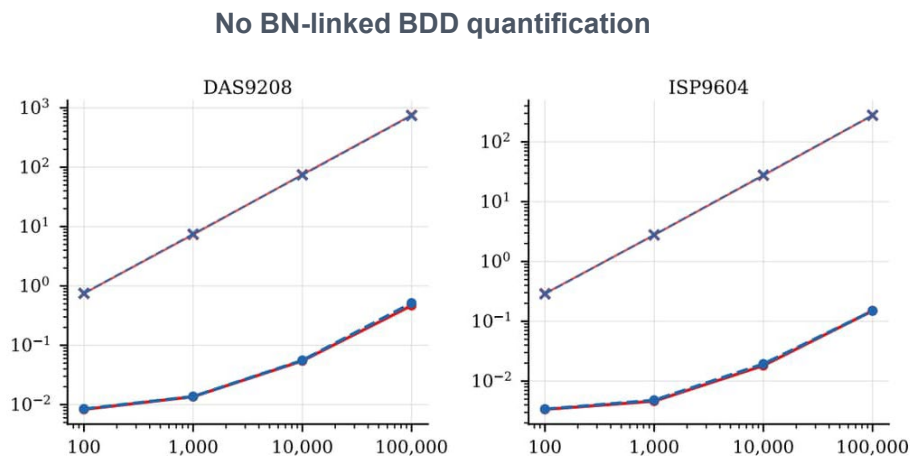
probability vector $\rightarrow$ HCL recursion

Vectorized UQ for BDD/HCL Quantification



□ : serialized ● : vectorized. I : # intersectional nodes, β : beta dist. shape parameter

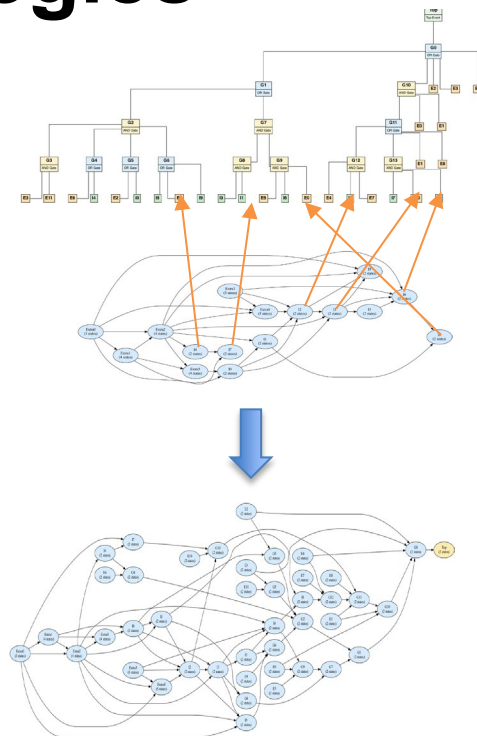
Gain : One to two orders faster;
BN oracle calls dominate runtime



X: serialized ● : vectorized. Gain: $\sim 1,500\text{--}1,900\times$ at $S = 10^5$

MAAT Verification Strategies

Verification matrix	
MAAT Component	Independent reference
Standalone FT / BDD quantification	Published FT benchmarks (e.g., Aralia)
BN-linked HCL point mode	Hand calculation+ equivalent unified BN
UQ mode	Equivalent unified BN
Event-tree module	SAPHIRE for ET-only; unified BN for BN-linked ET cases
PRA outputs	MCSs : MCUB vs exact HCL, SAPHIRE for no BN-linked Importance measures : published benchmarks and unified BN



Unified BN

Multi-Hazard BN Fragments to HCL Application Workflow

Multi-hazard BN fragments

- 1 Define BN layers for hazard dependency
- 2 Build hazard-field and propagation fragments
- 3 Represent HRA, damage, FLEX, and recovery logic

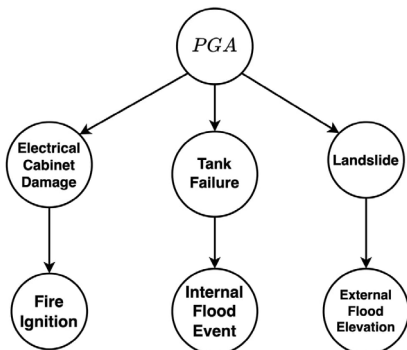
HCL coupling and workflow

- 4 Map BN outputs into the HCL integration scope
- 5 Couple PRA logic with BN and HCL policies
- 6 Quantify risk outputs, end state frequencies, MCS and importance measures

Sections: BN framework → hazard fields → HRA → damage → FLEX/recovery → HCL application workflow

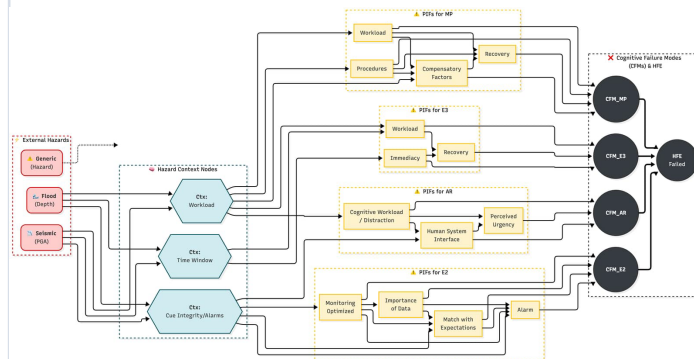
BN Fragments for Multi-Hazard PRA

Hazard fields



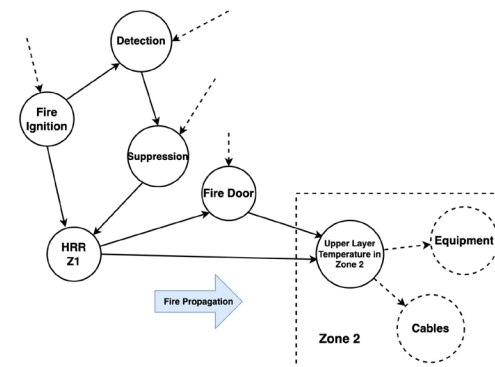
- Primary hazard state is represented by IM bins
- PGA can trigger fire, internal flooding, or external flooding pathways
- Secondary-hazard probabilities are conditioned on the primary hazard state

Human actions



- Hazard and plant states change workload, time pressure, and alarm conditions
- PIFs condition cognitive failure modes
- CFMs aggregate to the HFE probability used by HCL

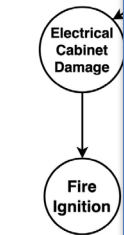
Hazard propagation



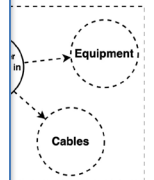
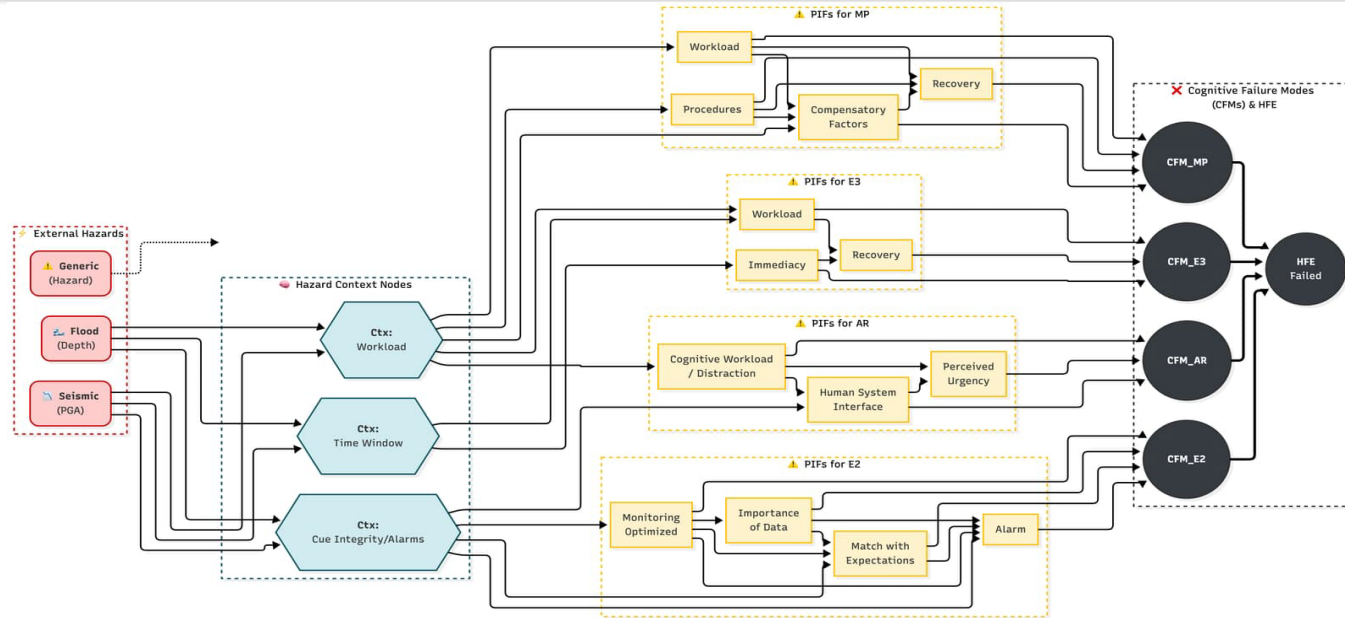
- Detection, suppression, and barriers shape fire propagation
- Propagation states determine target exposure
- Equipment or cable damage becomes a mapped PRA event

BN Fragments: HRA

Hazard fi



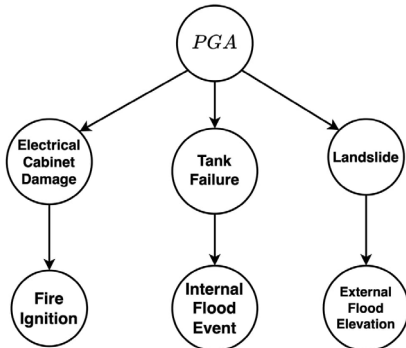
- Primary bins
- PGA ca
- externa
- Second
- conditi



riers shape
target
omes a

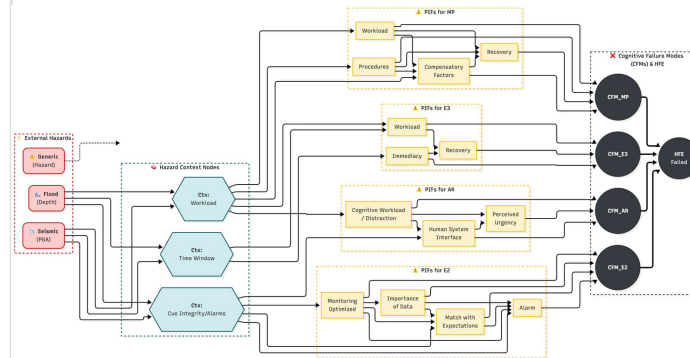
BN Fragments for Multi-Hazard PRA

Hazard fields



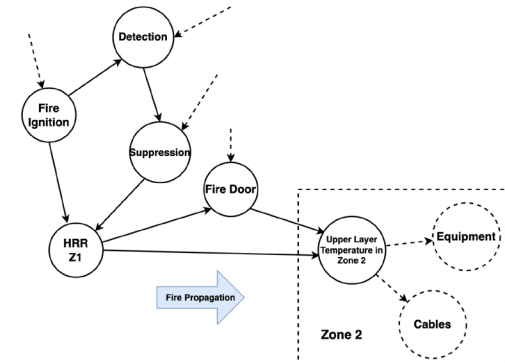
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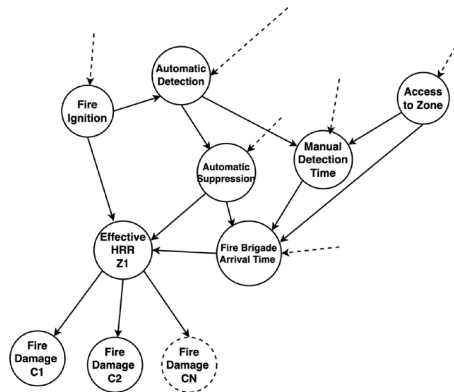
Hazard propagation



- Detection, suppression, and barriers shape fire propagation
- Propagation states determine target exposure
- Equipment or cable damage becomes an intersectional event

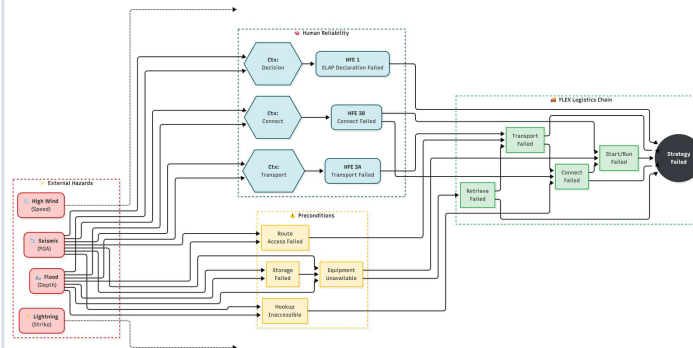
BN Fragments for Multi-Hazard PRA

Damage



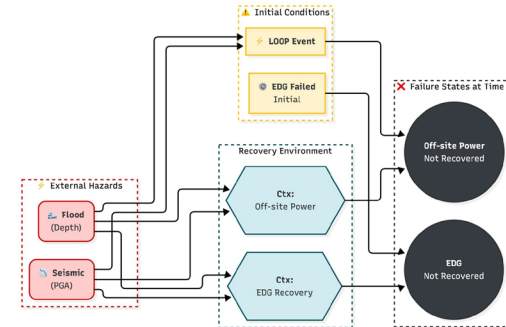
- Fire conditions determine effective HRR and target damage
- Detection, suppression, and access affect damage progression
- Damage is determined through a fragility function

FLEX deployment



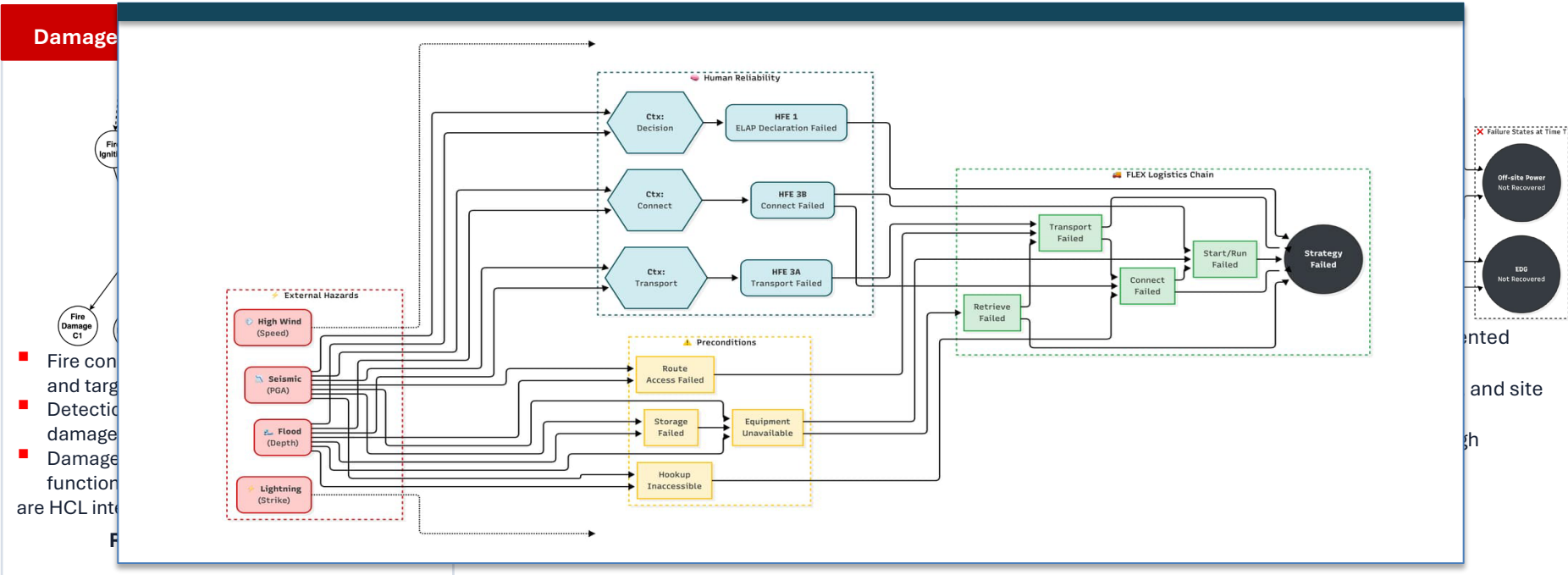
- FLEX is modeled as a deployment chain
- Portable equipment deployment under degraded conditions
- Storage survivability, route access, hookup feasibility
- FLEX success depends on survivability and deployment

Recovery



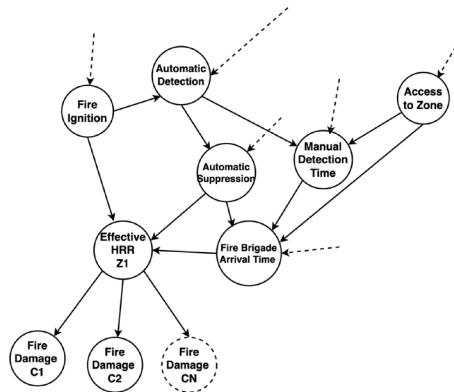
- LOOP and EDG recovery are tied to mission-time windows
- Damage state determines whether recovery is physically possible
- Access, debris, flooding, and work conditions shift recovery probability

BN Fragments: FLEX



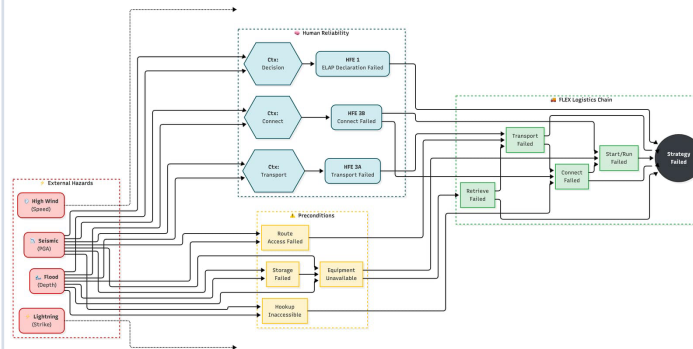
BN Fragments for Multi-Hazard PRA

Damage



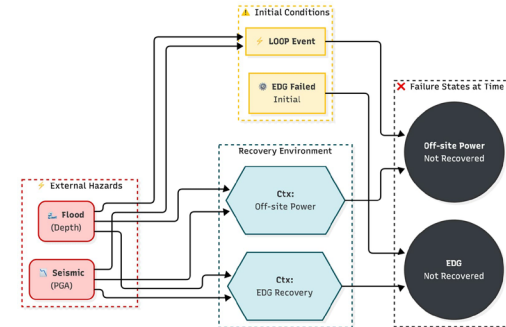
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Case Study Setup & Risk Insights

Case study setup

1

PRA model: LOOP → SBO → FLEX

2

BN sub-models connect seismic, flood, fire, recovery, FLEX, and HRA

3

Fire and coastal-defense hazard inputs

Results and interpretation

4

CDF shifts across the seismic–flood hazard matrix

5

Coastal-defense upgrade and FLEX credit reduce modeled risk

6

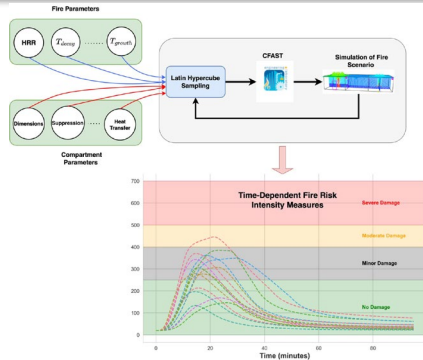
Sensitivity, UQ, and importance measures identify dominant drivers

Fire Hazard Modeling

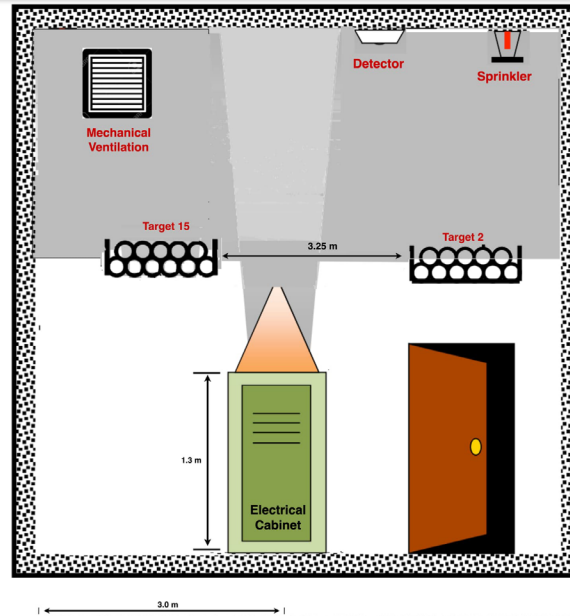
Scenario setup

- **Location:** 4.16 kV Switchgear Room A
- **Fire source:** vertical switchgear cabinet, HEAF-triggered ignition.
- **Targets:** two cable bundles on adjacent raceways.
 - Switchgear control/protection cables
 - Train A 4.16 kV power cable

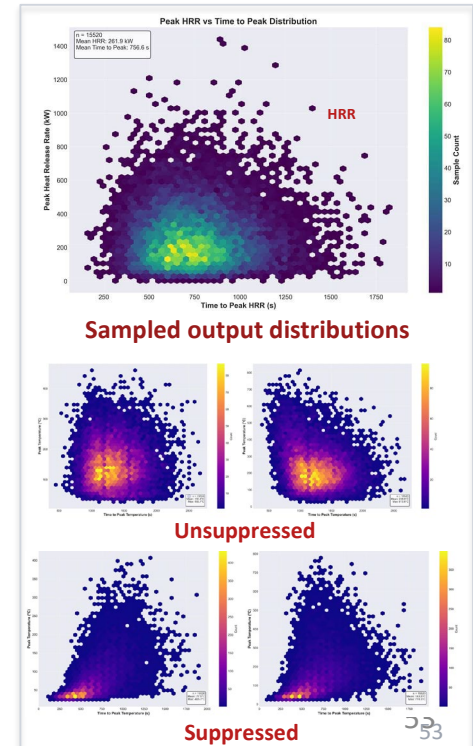
Fire Simulation in CFAST



Room Geometry and Targets



Ph.D. Final Exam



Importance Measures Analysis

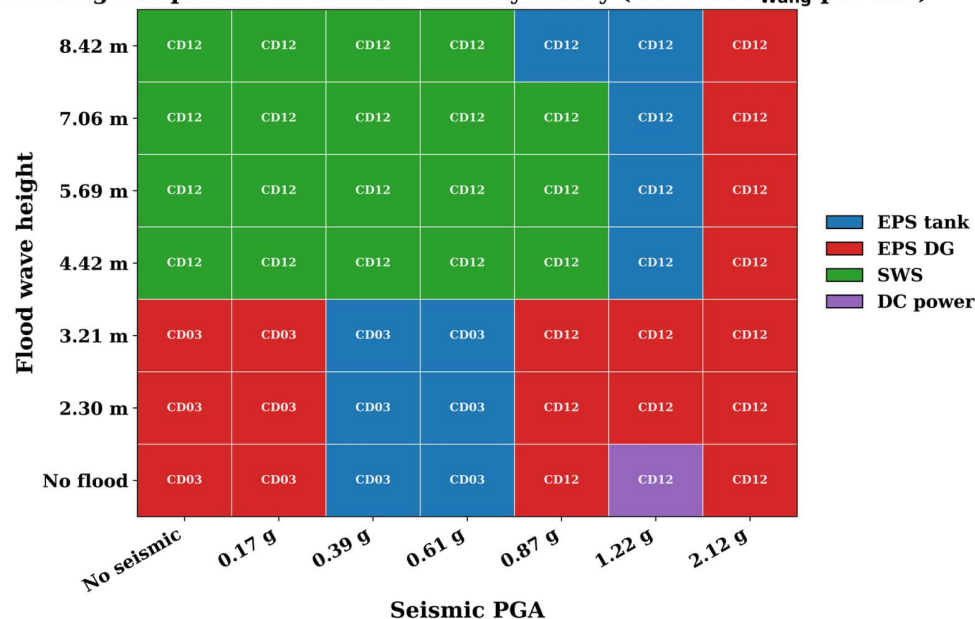
Importance measures used in this analysis

Define: $P_b = P(CD)$, $P_1 = P(CD|x = 1)$, $P_0 = P(CD|x = 0)$
 $x = 1$: event forced failed $x = 0$: event forced successful

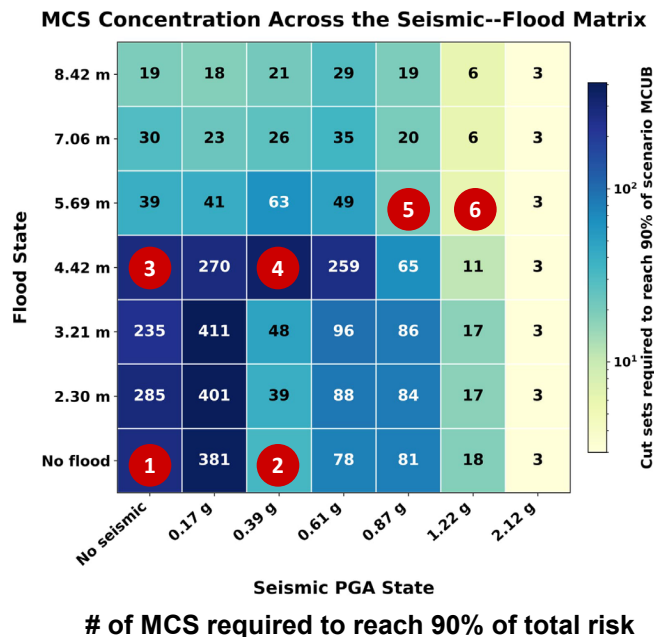
Measure	Equation	Meaning
FV	$FV(x) = \frac{P(x) P_1}{P_b}$	Share of CD probability associated with event x being failed
Birnbaum	$I_B(x) = P_1 - P_0$	Sensitivity to changing the event from success to failure.
RAW	$RAW(x) = \frac{P_1}{P_b}$	Risk penalty if the event is assumed failed.

$w_i^{CD} = \lambda_i P(CD|H_i) / \sum_i \lambda_i P(CD|H_i)$ $\bar{I}(x) = \sum_i w_i^{CD} I_i(x)$
 Weights each hazard cell by its contribution to total CD frequency.

Leading component-level basic event by family (rank-1 FV_{Wang} per cell)



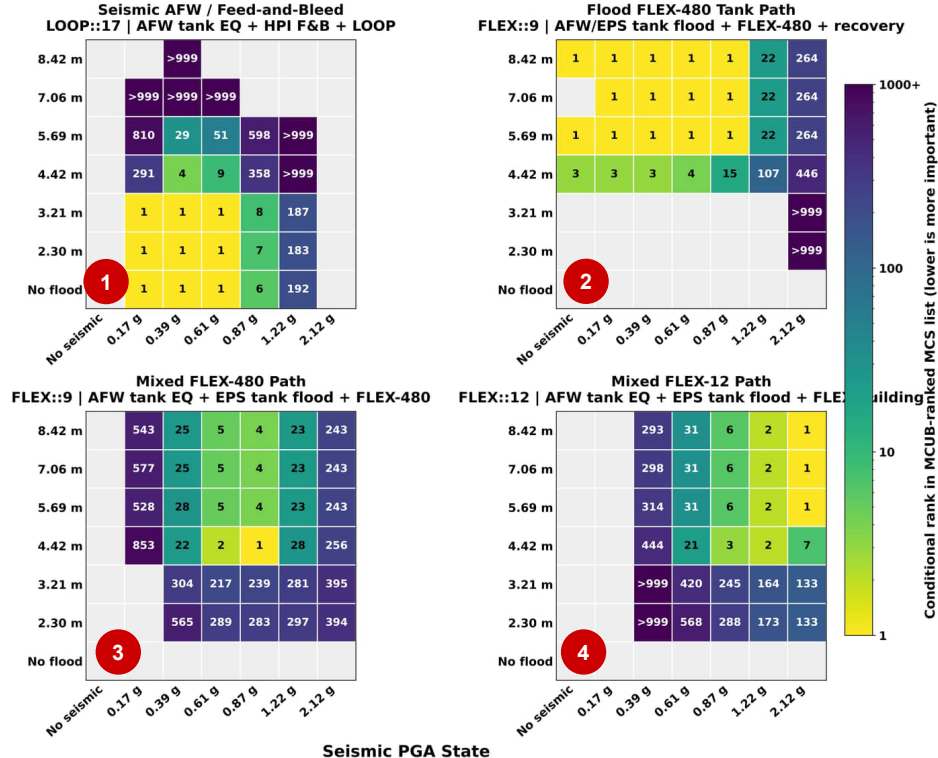
Minimal Cut Sets (MCSs)



Selected cell	Dominant MCS pattern
1 No hazards 268 8.4%	SBO::6 — DG fail-to-run + DG recovery failure + LOOP recovery failure
2 0.39 g, no flood 33 50.1%	LOOP::17 — AFW tank seismic + feed-and-bleed operator failure
3 W3, no seismic 271 8.8%	FLEX::9 — DC-panel/EPS tank flood failure + failed FLEX-480 deployment + failed DG/offsite power recovery.
4 0.39 g + W3 351 9.3%	FLEX::9 — DC-panel/EPS tank flood failure + failed FLEX-480 deployment + failed DG/offsite power recovery.
5 0.87 g + W4 21 22.2%	FLEX::9- AFW/EPS tank flood failure + failed FLEX-480 deployment + failed DG/offsite power recovery.
6 1.22 g + W4 6 39.6%	FLEX::12 — FLEX building failure + AFW/EPS tank flood failure + failed long-duration power recovery.

Selected MCS Ranks Across the Seismic–Flood Matrix

Conditional Rank of Selected Minimal Cut Sets



- LOOP::17 — seismic AFW / feed-and-bleed**
 AFW tank seismic failure + HPI feed-and-bleed failure + LOOP.
 Rank 1 in low-flood, moderate-seismic cells.
- FLEX::9 — flood FLEX-480 path**
 AFW/EPS tank flood + FLEX-480 failure + recovery failures.
 Rank 1 across W4–W6 at low-to-moderate PGA.
- FLEX::9 — mixed seismic–flood FLEX-480 path**
 AFW tank seismic failure + EPS tank flood + FLEX-480 failure + failed recovery.
 Middle region: 0.61–0.87 g and 4.42–5.69 m.
- FLEX::12 — severe mixed-hazard path**
 AFW tank seismic failure + EPS tank flood + FLEX building/equipment seismic failures + failed long-duration recovery.
 Rank 1 or 2 in severe combined-hazard cells.

Rank of cut sets changes with the hazard state.

Future Work

Multi-block ordering policy

Partition intersectional events into smaller blocks using conditional independence. Carry only the boundary information needed for later BN queries.

Goal: limits context growth when intersectional nodes increase.

Multi-unit PRA (MUPRA)

Represent multiple reactor units with shared support systems, common electrical infrastructure, common hazard exposure, and site-level recovery constraints.

Goal: moves HCL from unit-level analysis toward site-level risk.

Time-dependent HCL

Extend the BN layer into time slices (Dynamic BNs) to represent hazard order, recovery windows, and changing plant/site conditions.

Aftershock sequence modeling

Model aftershock occurrence and intensity conditional on the mainshock and the time window. Aftershocks impact recovery actions

Example: Epidemic-Type Aftershock-Sequence (ETAS) model