Dynamic PRA of a Multi-unit Plant

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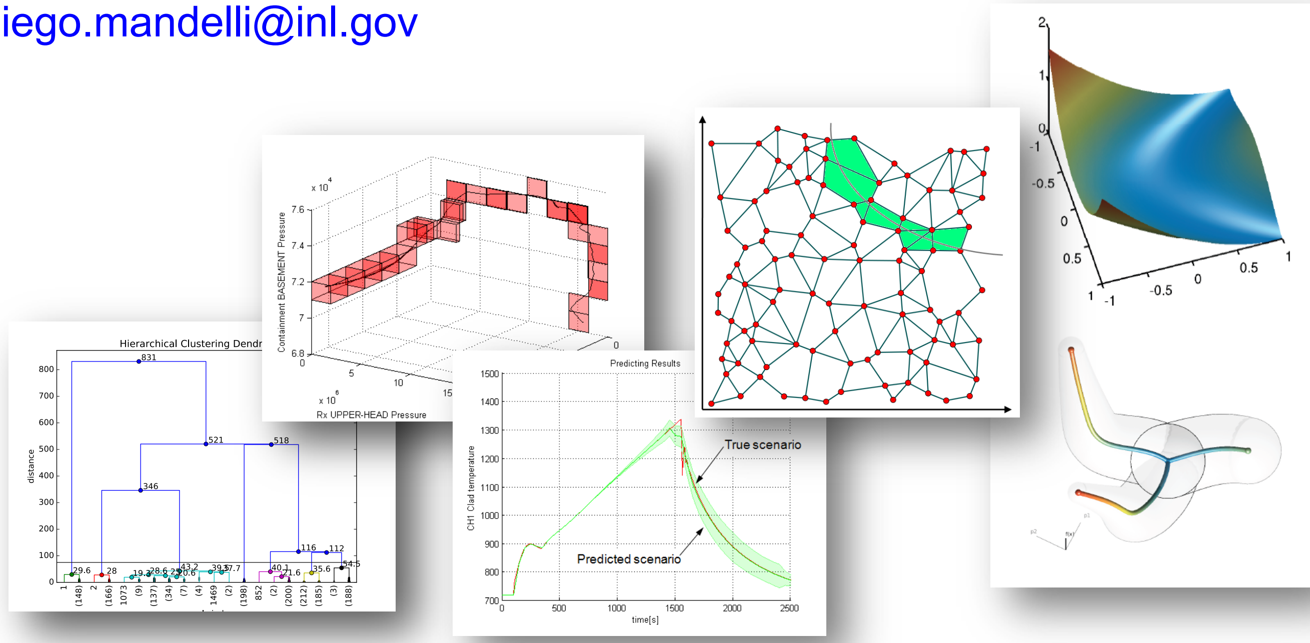
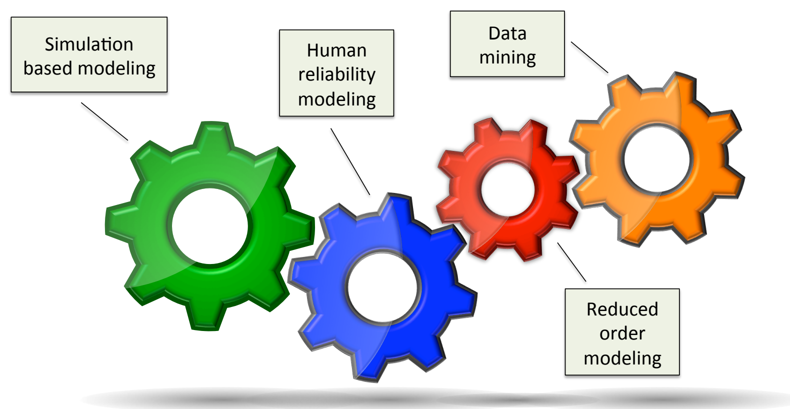


IRUG Meeting – Idaho Falls, April 18th 2019

Multi-Unit Analysis: Overview

- Objectives: perform an integral multi-unit plant analysis using a simulation-based approach
  - Timing/sequencing of events among units
  - Large variety of interdependencies

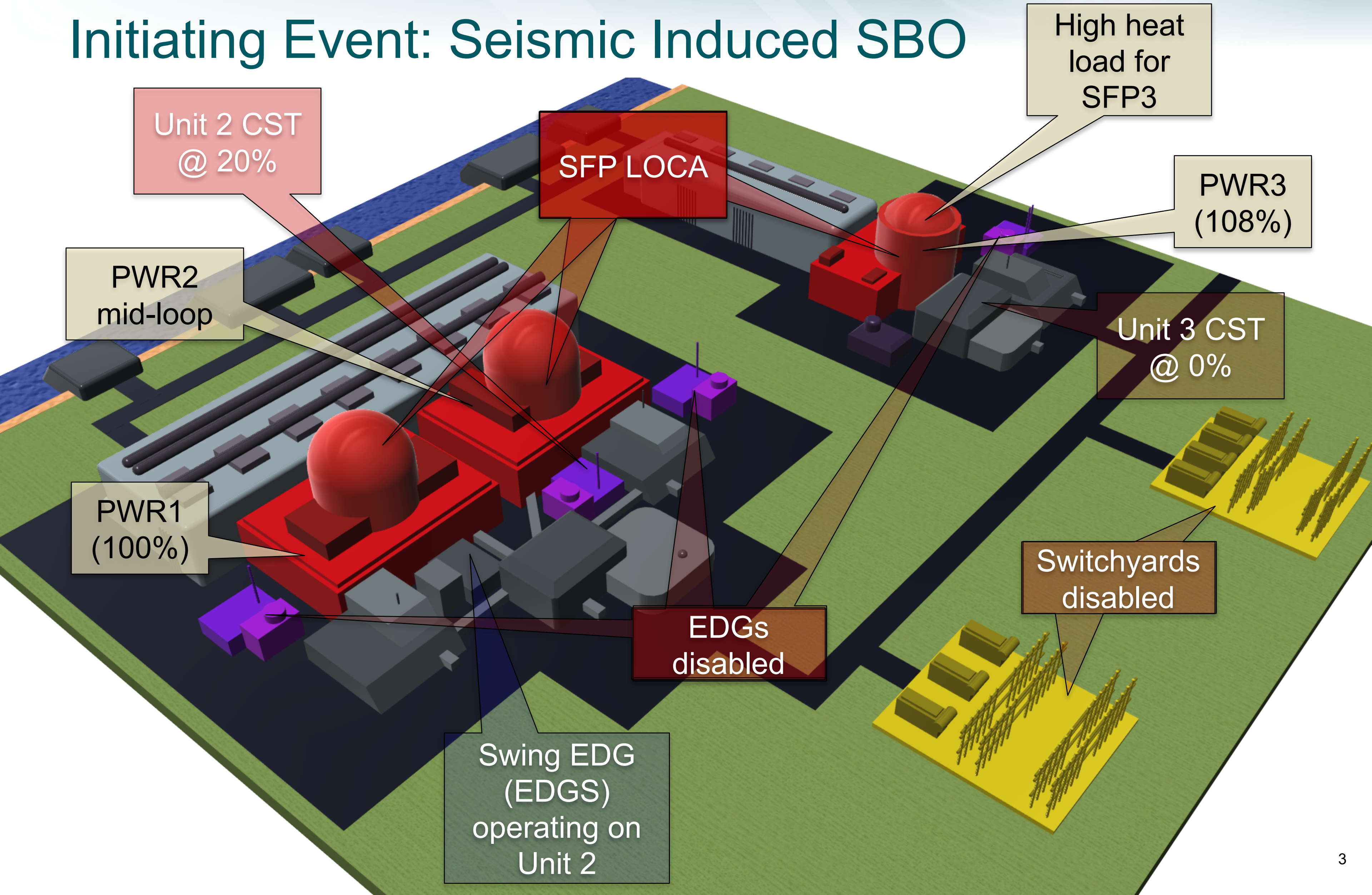


- Analysis summary:
  - TH modeling of PWRs and Spent Fuel Pools (SFPs)
  - Human reliability models (HUNTER)
  - Dynamic PRA
  - Modeling of control logic at the site level
  - Heavy use of Reduced Order Models (ROMs)
  - Data analysis of large and complex dataset

RELAP5-3D

RAVEN

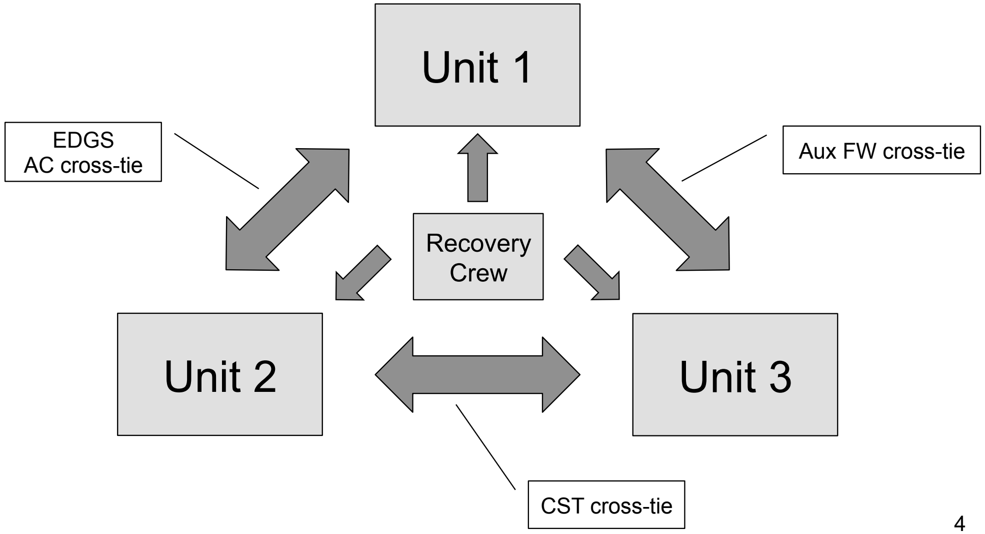
Initiating Event: Seismic Induced SBO



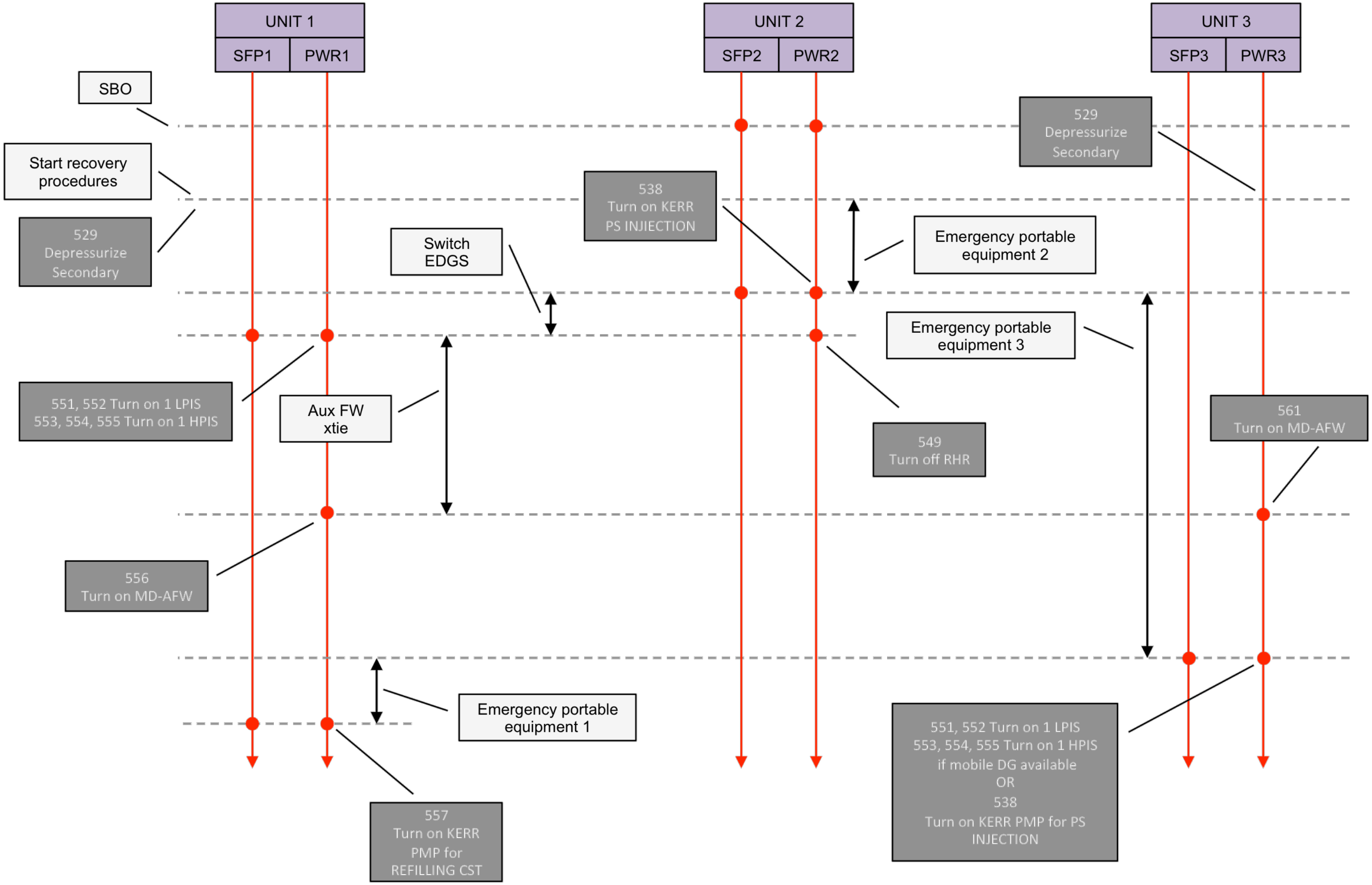
Plant and Recovery Actions

- Unit dependencies:
  - Plant electrical system (EDGS) and AC cross-tie
  - AFW and CST cross-ties
  - Plant recovery crew, Emergency Portable Equipment (EPE)

- 3 formulated recovery strategies:
  - Sequence of unit recovery based on a prioritization scheme
    - Depending on unit status
    - One unit at a time
  - Sequence might change depending on accident progression
    - e.g., erroneous alignment of EDGS

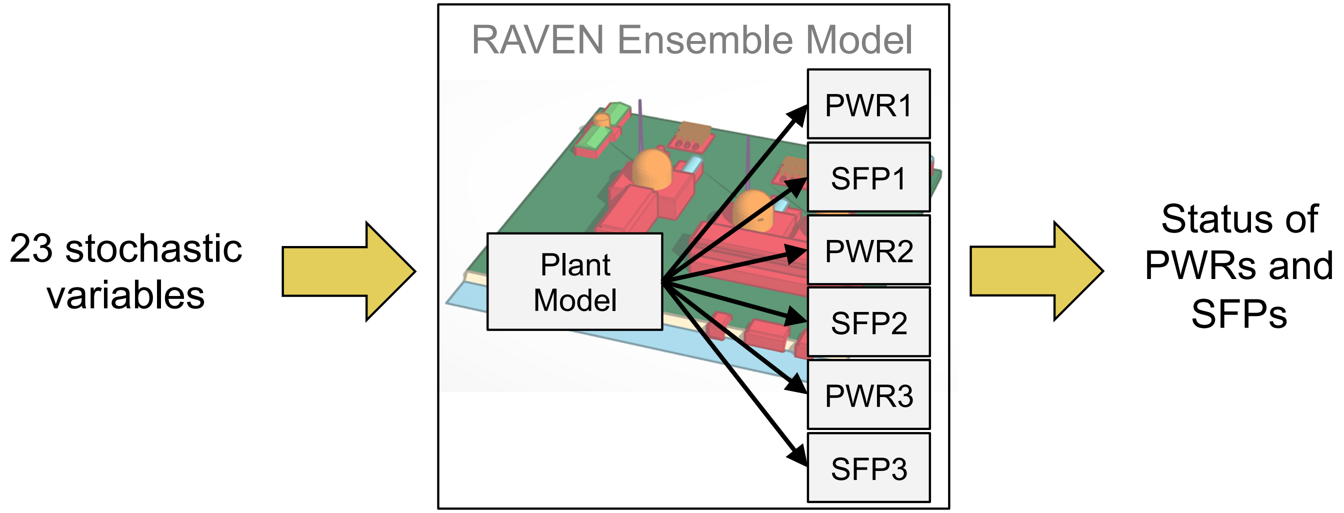


Accident Progression: Example



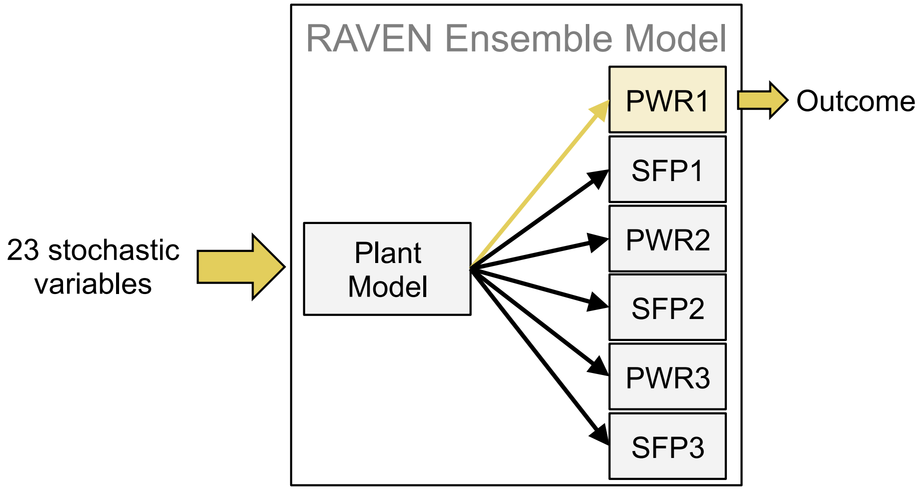
RISMC Multi-Unit Modeling

- 23 stochastic variables:
  - Timing of events
  - Recovery actions
  - Human interventions
- Site deterministic model:
  - RAVEN Ensemble model
- Plant model:
  - RAVEN external model
  - Handle plant and recovery control logic
  - Human reliability models included
  - Determine timing of events for all 6 models given values of 23 sampled parameters
- HRA methods:
  - HUNTER: sub-task modeling
  - THERP: EDGS erroneous alignment



ROM Modeling

- Multi-unit analysis issues:
  - Large computational cost
  - High probability of simulation crash
- Solution: employ ROMs
  1. Sample code response
  2. Choose and train ROM
  3. Validate ROM response

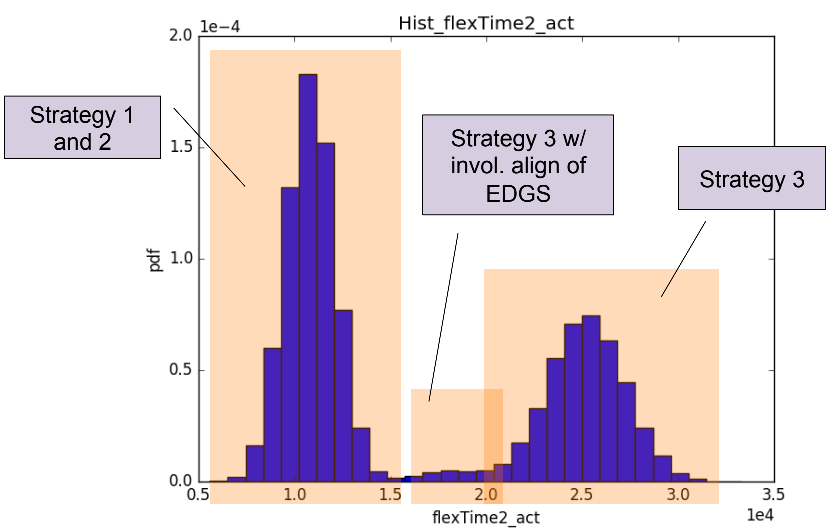


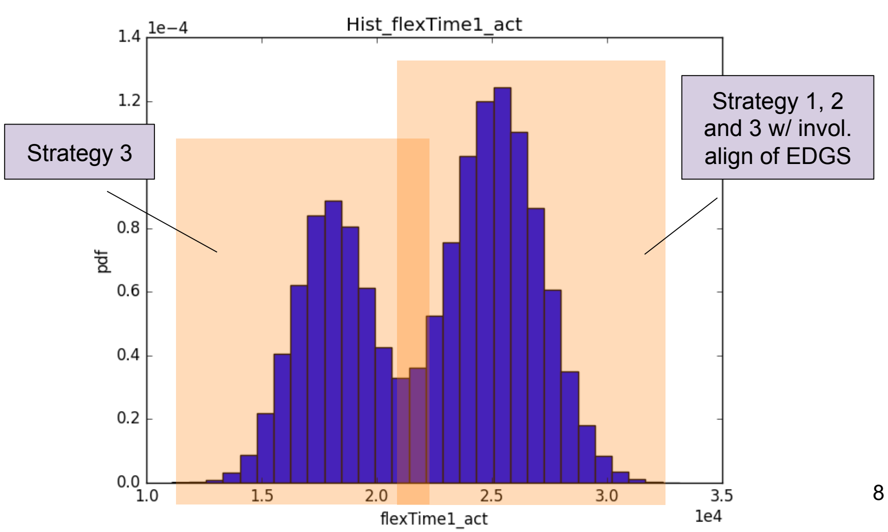
- ROM employed: KNN
  - Prediction performed by considering *K* neighbor samples
  - *K* is chosen based on validation results (3-fold validation process)
- Training samples size chosen based on convergence prediction

Model	Parameter Count	Optimal k	Training size	Validation size	Prediction accuracy (%)
PWR1	7	5	4596	2500	100.0
PWR2	3	25	4951	2662	99.36
PWR3	10	50	12000	5988	100.0
SFP1	3	5	2883	2876	99.72
SFP2	5	5	4695	4714	99.02
SFP3	3	5	2807	2817	99.04

Multi-Unit PRA

- Approach: Monte-Carlo
  - 1.1 M samples
- For each simulation the outcome of each model/ROM is collected
  - OK or failed
- Such a large coupling among units strongly affects timing and sequencing of events
  - Valid even from a probabilistic point of view
  - Here classical tools show their limitations





Data Analysis

- CD probability is typically determined for a single model (PWR or SFP)
- At a plant level, a probability value is associated to a Plant Damage State (PDS)
- A PDS is a 6-dimensional vector:
  - Each vector element describes the status of a model (OK or CD)
  - Vector elements are highly correlated
  - $2^6 = 64$ PDSs allowed
- Approach:
  1. Group simulation runs based on their own PDS
  2. Evaluate probability associated to each PDS and rank PDSs based on their probability values.
  3. Identify commonalities that characterize each PDS

Results

- 14 out of 64 PDSs were actually generated

ID	PDS						Probability		
	PWR1	PWR2	PWR3	SFP1	SFP2	SFP3	mean	5^{th}	95^{th}
8	OK	OK	CD	OK	OK	OK	0.890199555	0.889684864	0.890713359
12	OK	OK	CD	CD	OK	OK	0.058915971	0.058529164	0.059303781
10	OK	OK	CD	OK	CD	OK	0.033966983	0.033669558	0.034265467
9	OK	OK	CD	OK	OK	CD	0.012604994	0.012422046	0.012789049
24	OK	CD	CD	OK	OK	OK	0.002102999	0.002028218	0.002178912
13	OK	OK	CD	CD	OK	CD	0.001172999	0.001117271	0.001229862
14	OK	OK	CD	CD	CD	OK	0.000581	0.00054194	0.000621195
11	OK	OK	CD	OK	CD	CD	0.000165	0.000144457	0.00018668
26	OK	CD	CD	OK	CD	OK	0.000156	0.000136041	0.000177095
28	OK	CD	CD	CD	OK	OK	0.000111	9.43E-05	0.000128878
25	OK	CD	CD	OK	OK	CD	1.10E-05	6.17E-06	1.70E-05
15	OK	OK	CD	CD	CD	CD	6.00E-06	2.61E-06	1.05E-05
30	OK	CD	CD	CD	CD	OK	5.00E-06	1.97E-06	9.15E-06
29	OK	CD	CD	CD	OK	CD	1.00E-06	5.13E-08	3.00E-06

Results

CST is intact + multiple recovery actions available

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PWR3 can be recovered only within 50 min after SBO condition

Results

SFP LOCAs are present but recovery actions are able to mitigate them

SFP LOCAs are modeled through 2 stoch. params:

- SFP Loca time
- SFP Loca size

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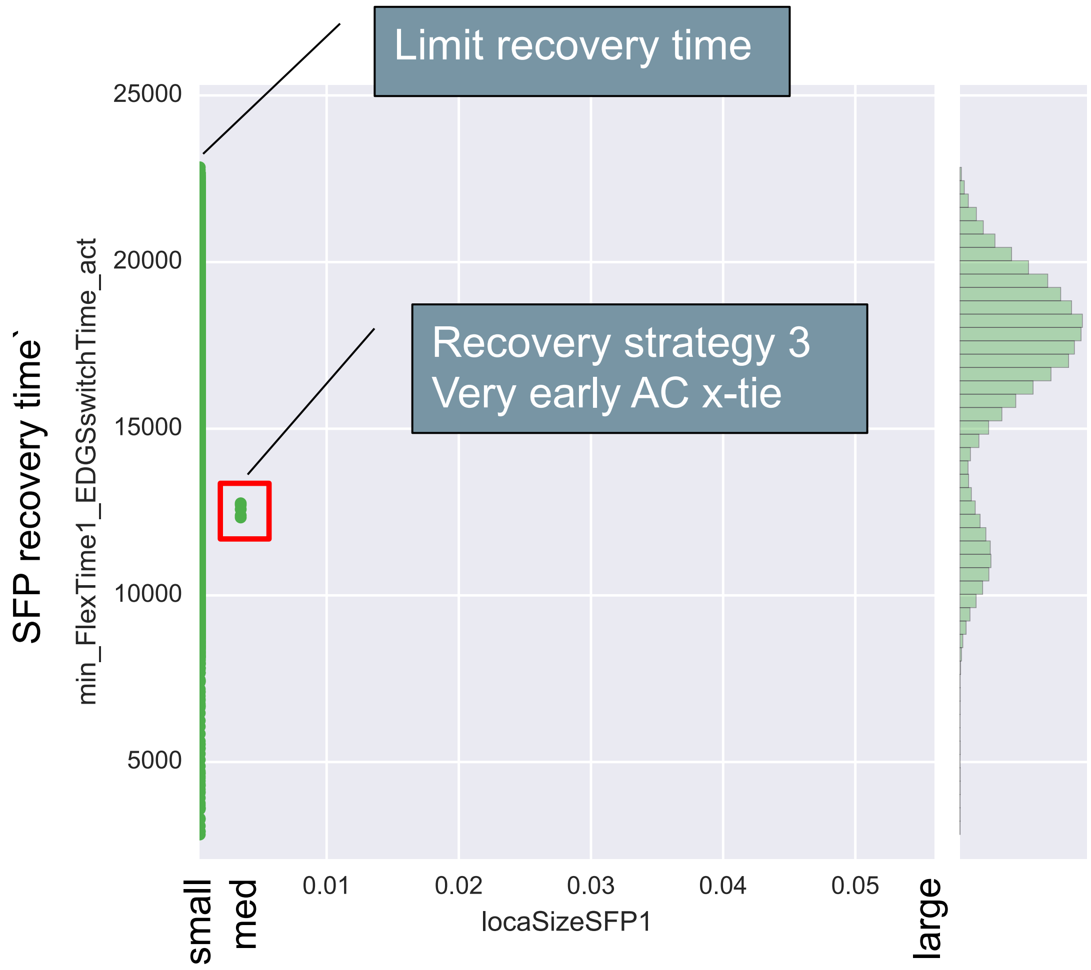
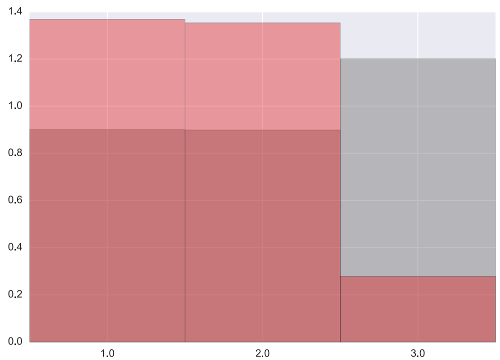
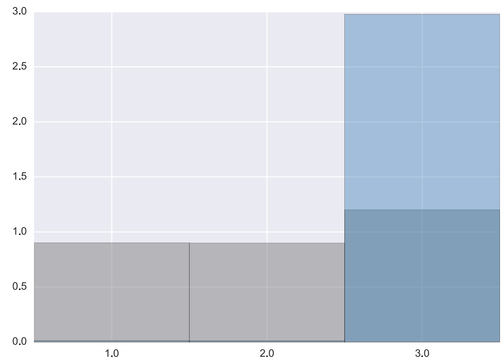
Results

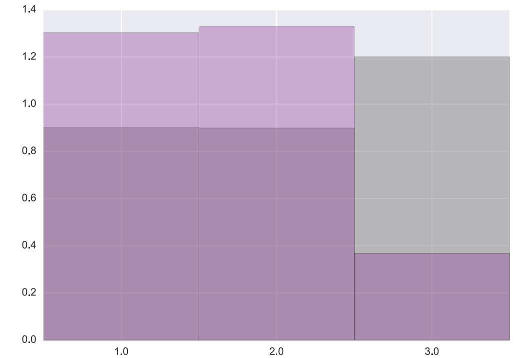


Limit recovery time
Recovery strategy 3
Very early AC x-tie
SFP recovery time`
min_FlexTime1_EDGSswitchTime_act
25000
20000
15000
10000
5000
small
med
0.01
0.02
0.03
0.04
0.05
large
locaSizeSFP1

Results







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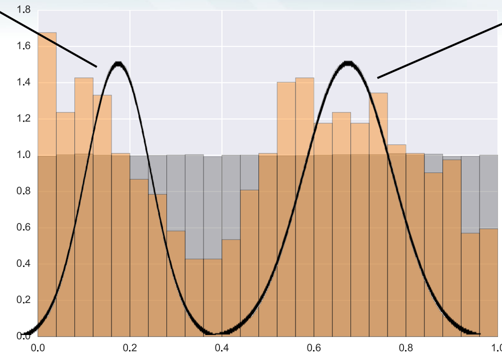
29	OK	CD	CD	CD	OK	CD	1.00E-06	5.13E-08	3.00E-06

Results

EPE on Unit 3

EPE on Unit 1



EDGS involuntary alignment time

Recovery strategy 3
Involuntary alignment of EDGS

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Summary

- First step toward a simulation-based approach to analyze multi-unit plants
- Focus on recovery actions
  - No additional failures were introduced in the analysis
- Scope
  - Identify optimal recovery actions
- Future work
  - Extend analysis to Level 2 analysis