INL/MIS-20-58628-Revision-0

Dynamic Force-on-Force Modeling Research

May 2020

Robby Christian, Steven R Prescott, Vaibhav Yadav, Shawn W St Germain

Changing the World's Energy Future

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LWRS Physical Security Pathway

Dynamic Force-on-Force Modeling Research

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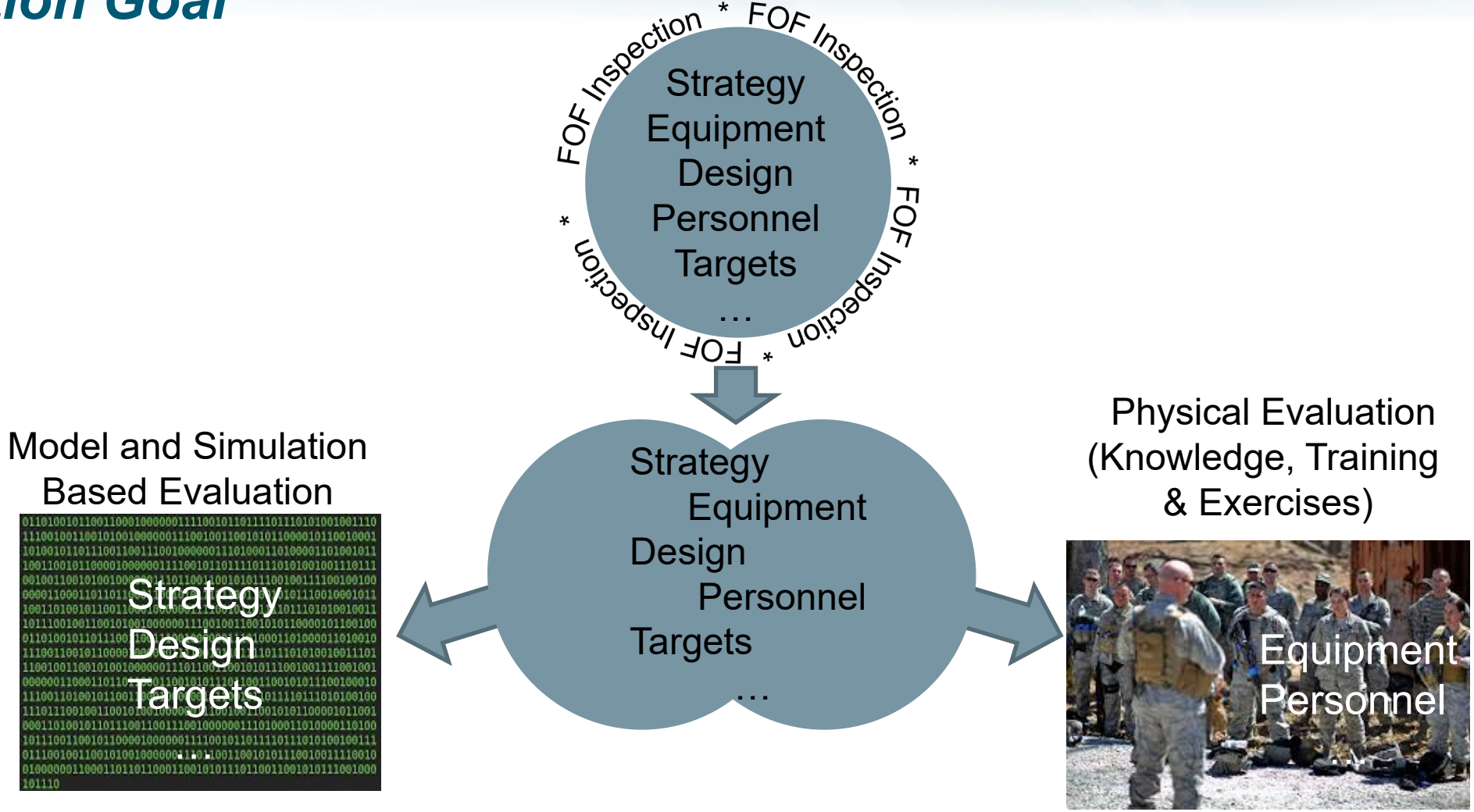
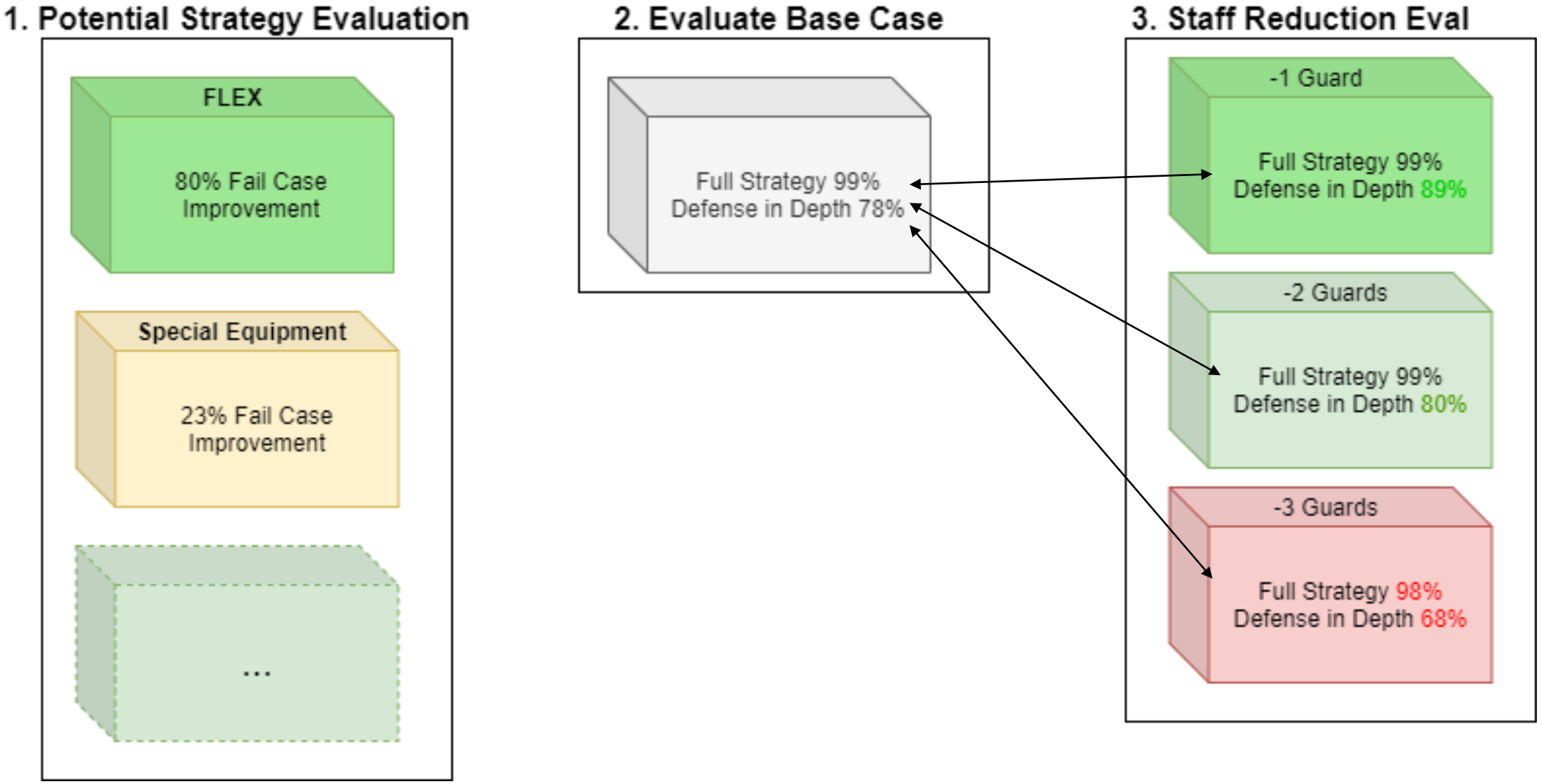
Research Objective

- Develop and demonstrate tools for a risk-informed physical security method by
  - Dynamic risk methods,
  - FLEX portable equipment
  - Physics-based modeling and simulation
  - Operator actions
  - Tie with existing PRA models
- The enhanced dynamic modeling capabilities will enable an optimized physical security posture with
  - Reduced uncertainties and conservatism
  - Increased realism in FoF models
  - Quantitative metrics that reflect risk-informed measures of effectiveness
  - Improved technical basis for plant physical security

Evaluation Goal

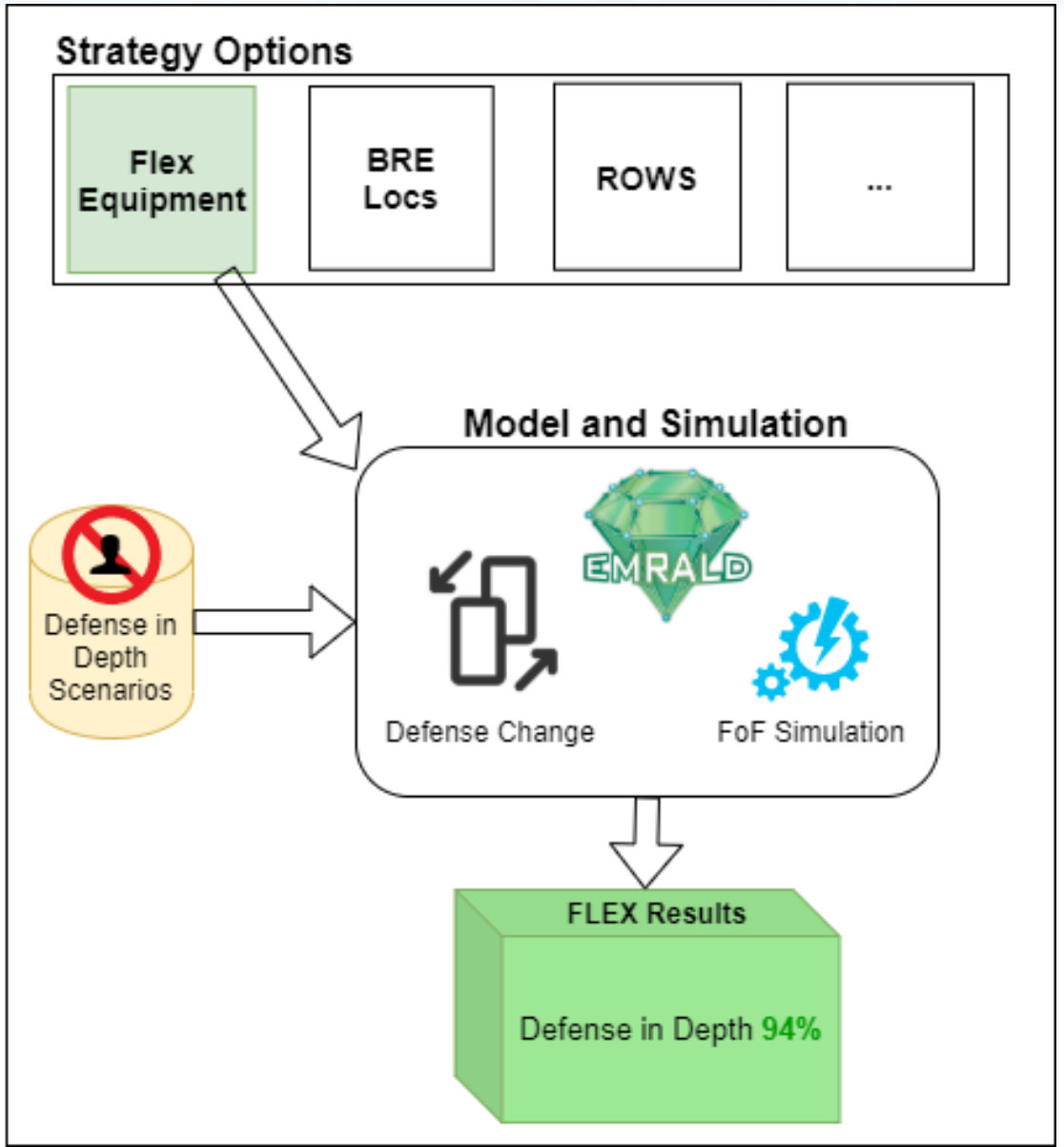


Change Evaluation Steps (Example)



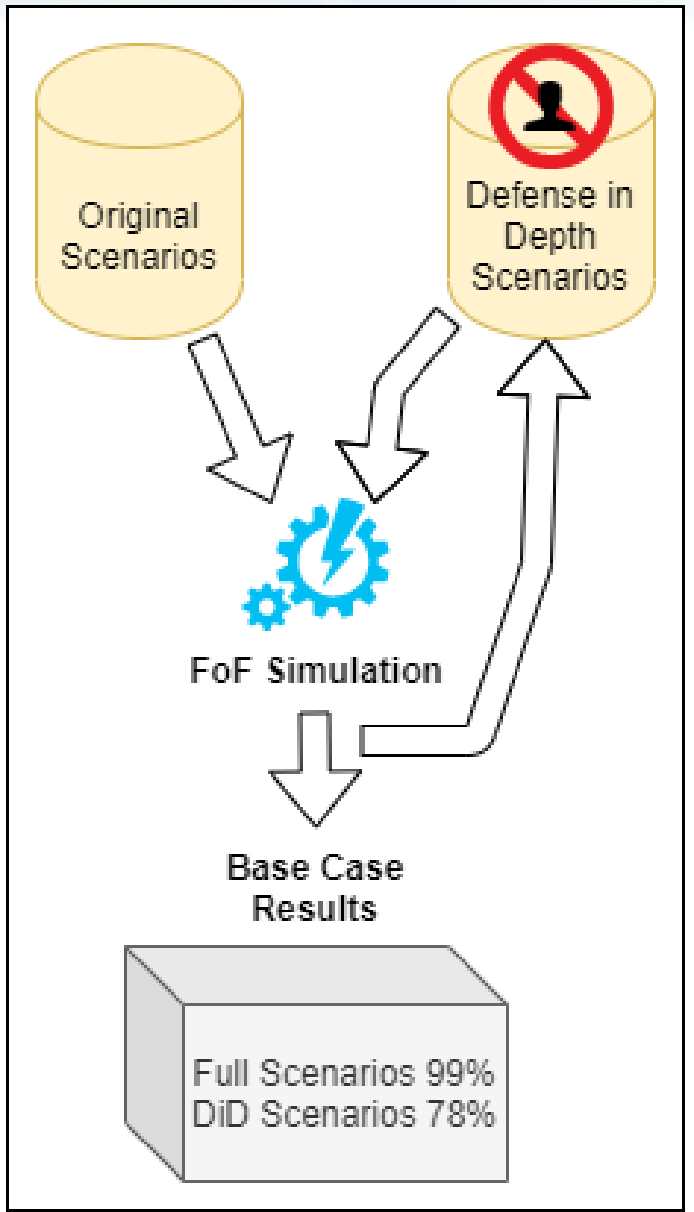
Potential Strategy Evaluation

1. Use research results and expert judgement to select strategy
2. Build model of Strategy using necessary tools
3. Use DiD scenarios from base results for varied data sets
4. Run simulations
5. Evaluate results for large increase in safety margin



Evaluate Base Case

1. Plant specific probable scenarios
2. Run Force-on-Force simulation for original
3. Save “Full Scenario” results
4. Remove “Best” guard for Defense-in-Depth (DiD) evaluation
5. Run Force-on-Force simulation for DiD
6. Save DiD results

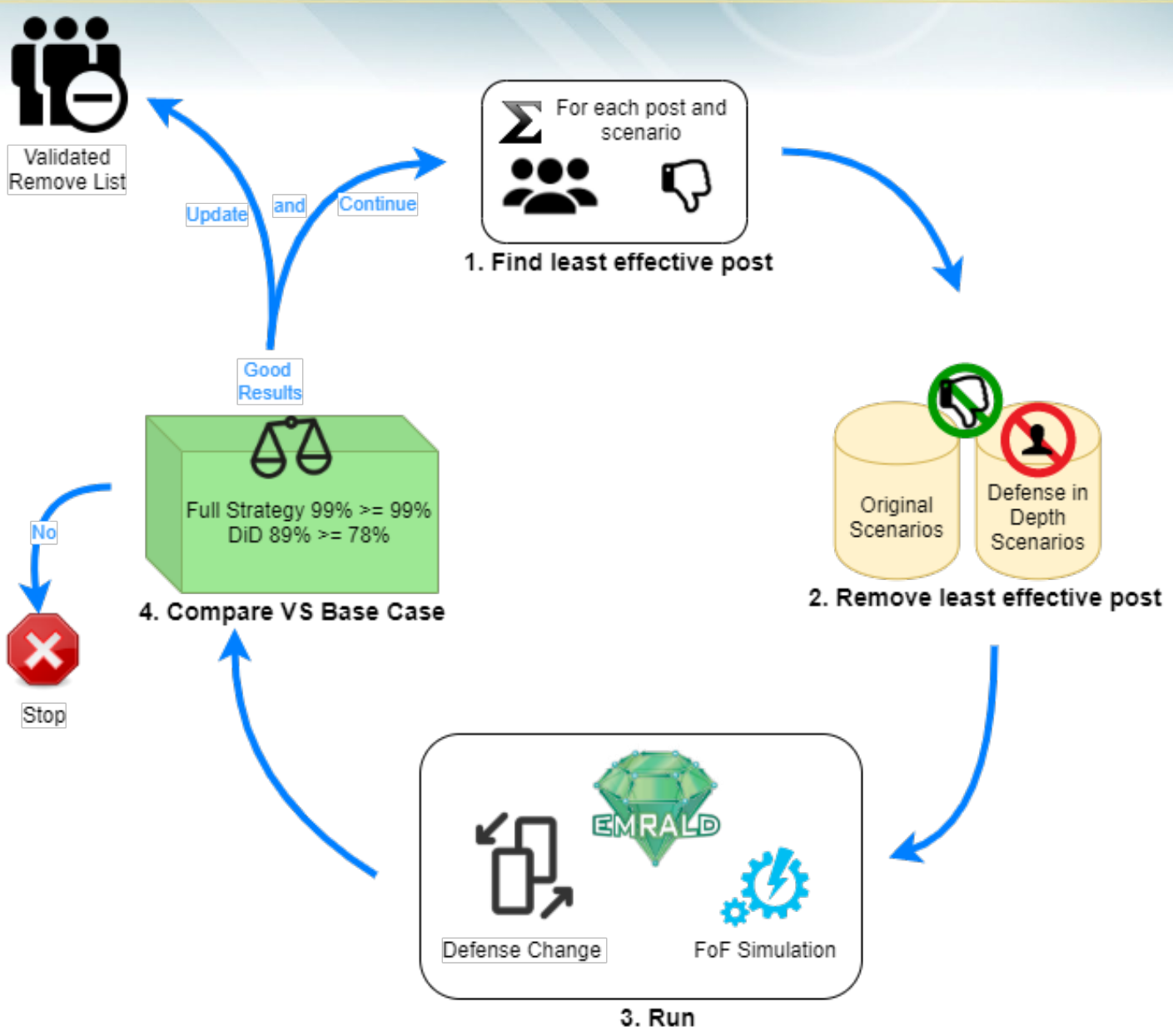


Staff Reduction Evaluation

For Each Strategy

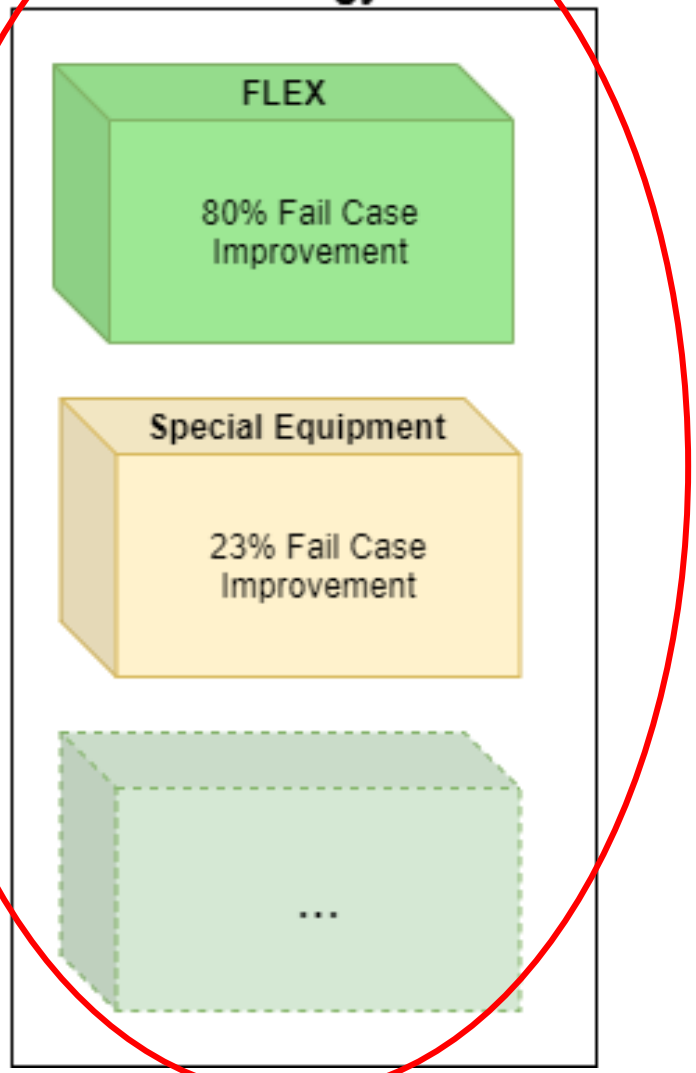
1. Determine least effective post for all scenarios
   - Use DiD scenarios
   - Normalize results
2. Remove lease effective from scenarios
3. Run modified scenarios with defense change models
4. Compare results (< Base Case)
   - Yes – Stop
   - No
     a) Add removed post to list
     b) Loop again for next post

When done validated remove list has post that can be eliminated because of defense strategy change.

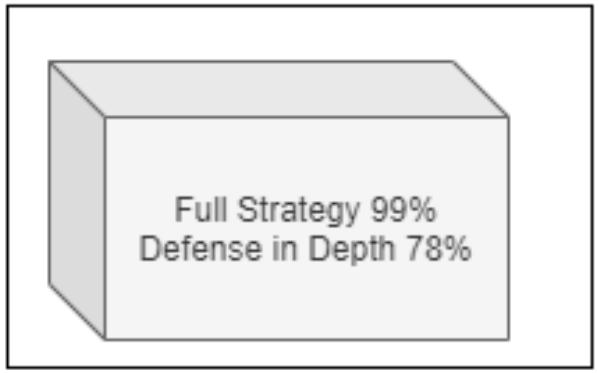


FY 2020 Focus

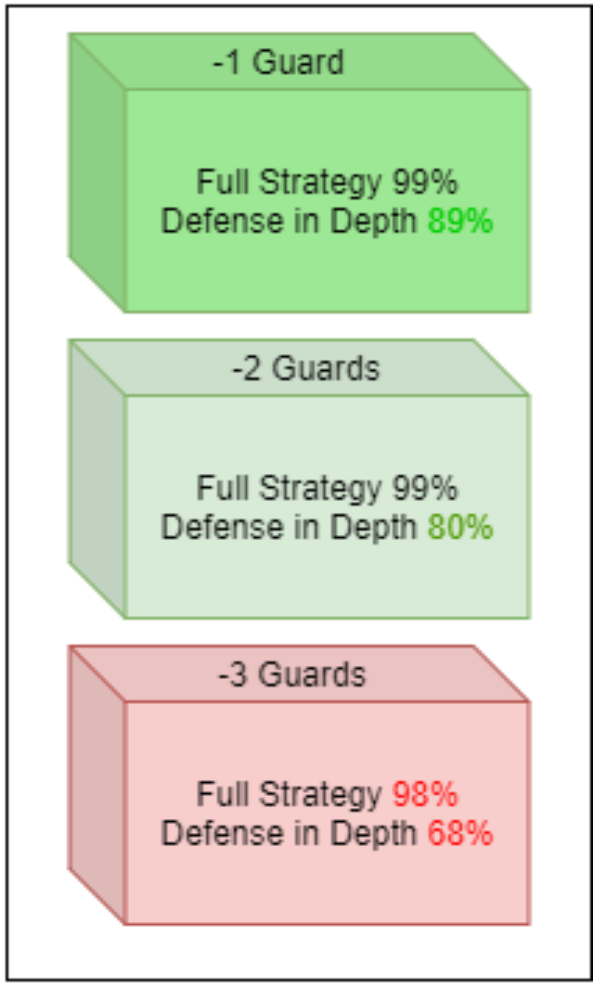
1. Potential Strategy Evaluation



2. Evaluate Base Case



3. Staff Reduction Eval



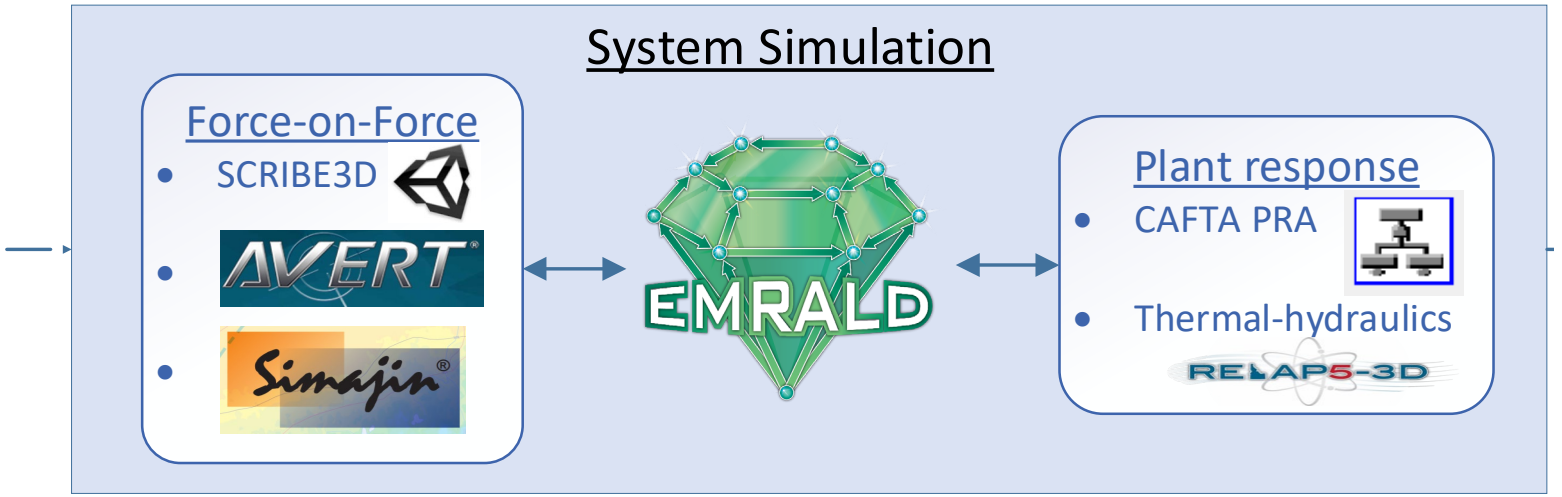
Simulation Tools and Optimization Areas

Tools

- Scribe 3D
- Avert
- Samajin
- EMRALD

Optimization Areas

- Human Performance Modeling
- Modeling Limitations
- Equipment & design Evaluation
- Flex Equipment
- BRE Optimization



EMRALD

(Event Model Risk Assessment using Linked Diagrams)

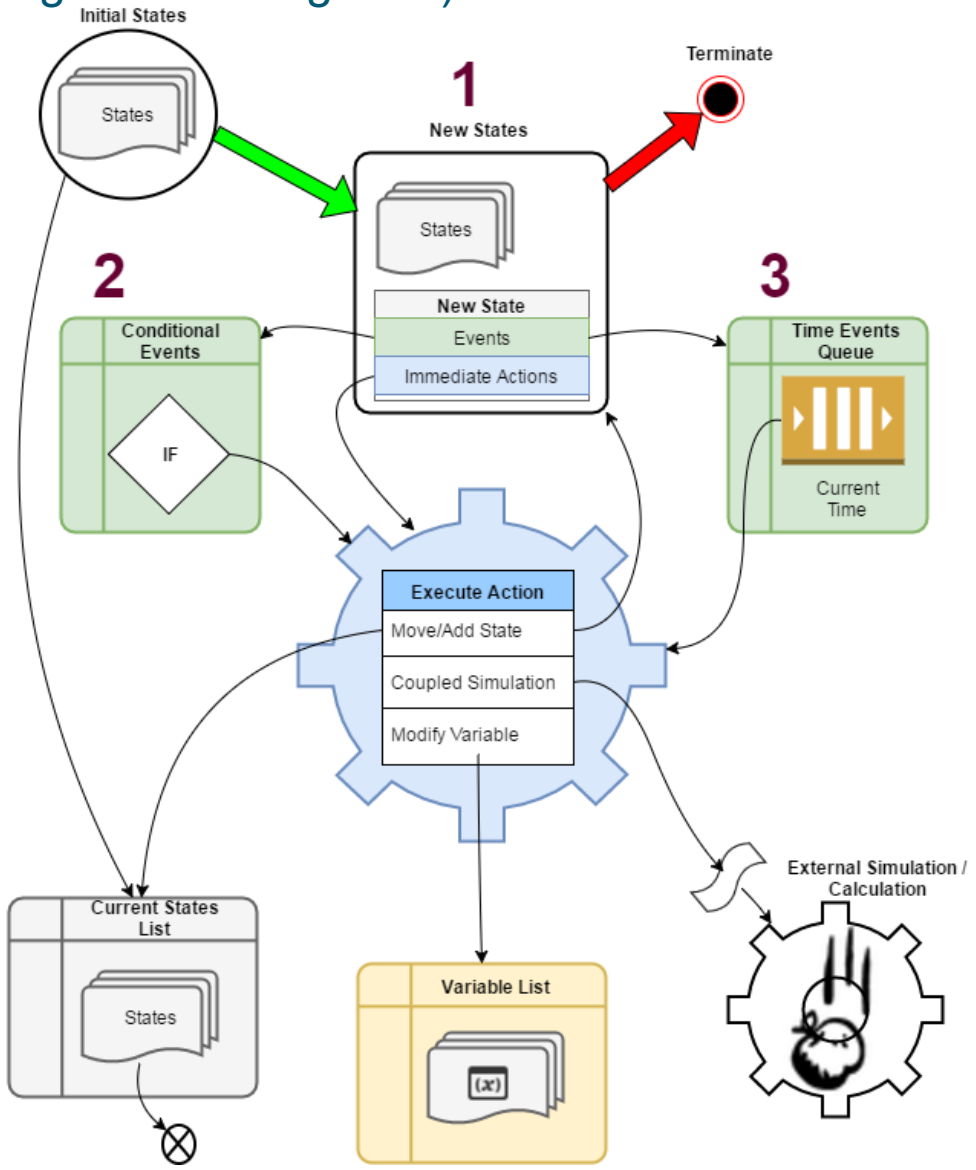
- Dynamic probabilistic risk assessment (PRA) model based on a three-phased discrete event simulation.

  To begin, add initial start states to Current and New States List.

  1. While there are States in the New States list, For each State :
     - Add the Events to the Time Queue or Conditional List.
     - Execute any Immediate Actions

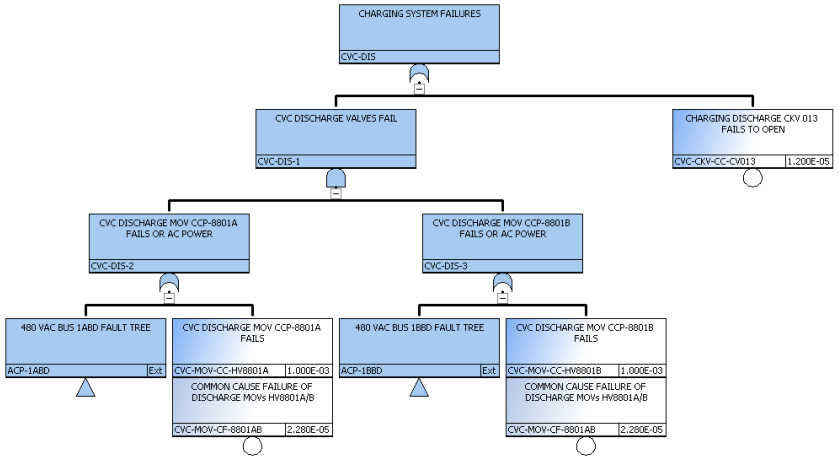
  2. If any Conditional Events criteria is met.
     - Execute that events action/s.
     - (Go to Step 1)

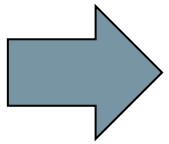
  3. Jump to the next chronological event.
     - Process that event's actions.
     - (Go to Step 1)

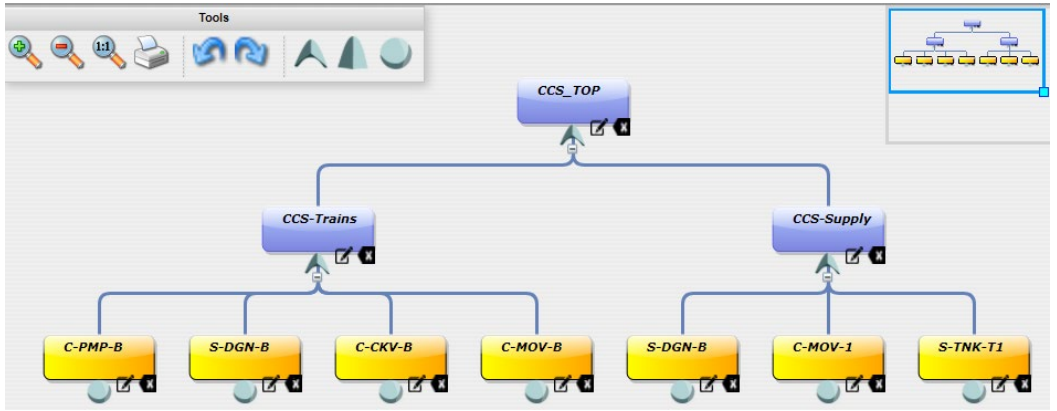


Why EMRALD

1. Combination of dynamic with traditional modeling techniques
2. Industry use focus for UI vs. scientific research





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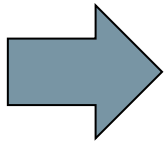
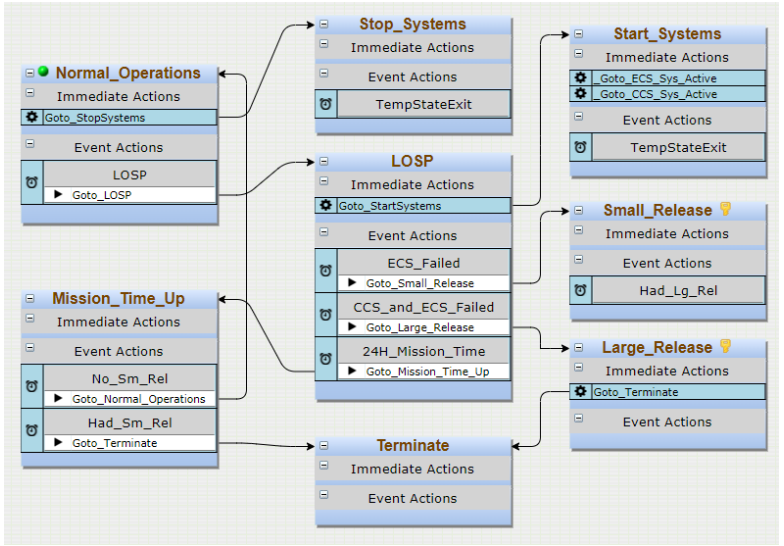
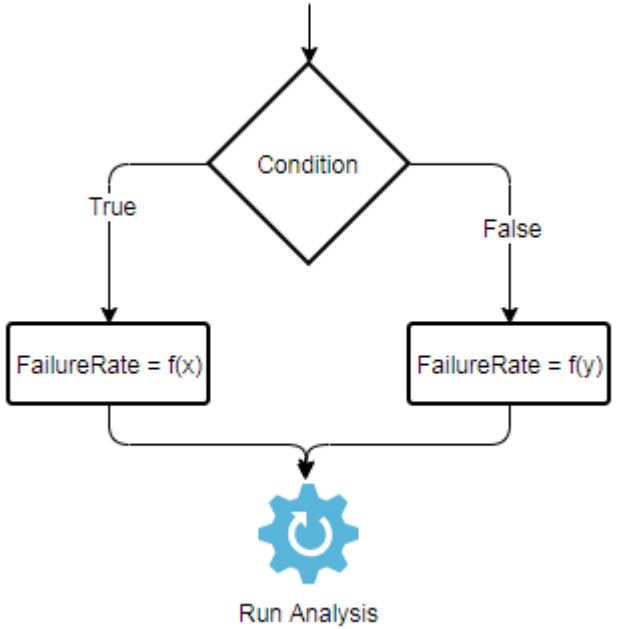
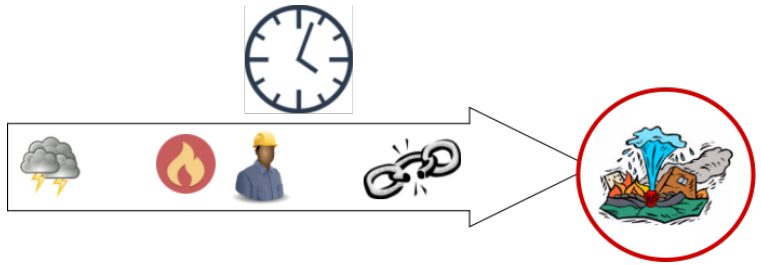


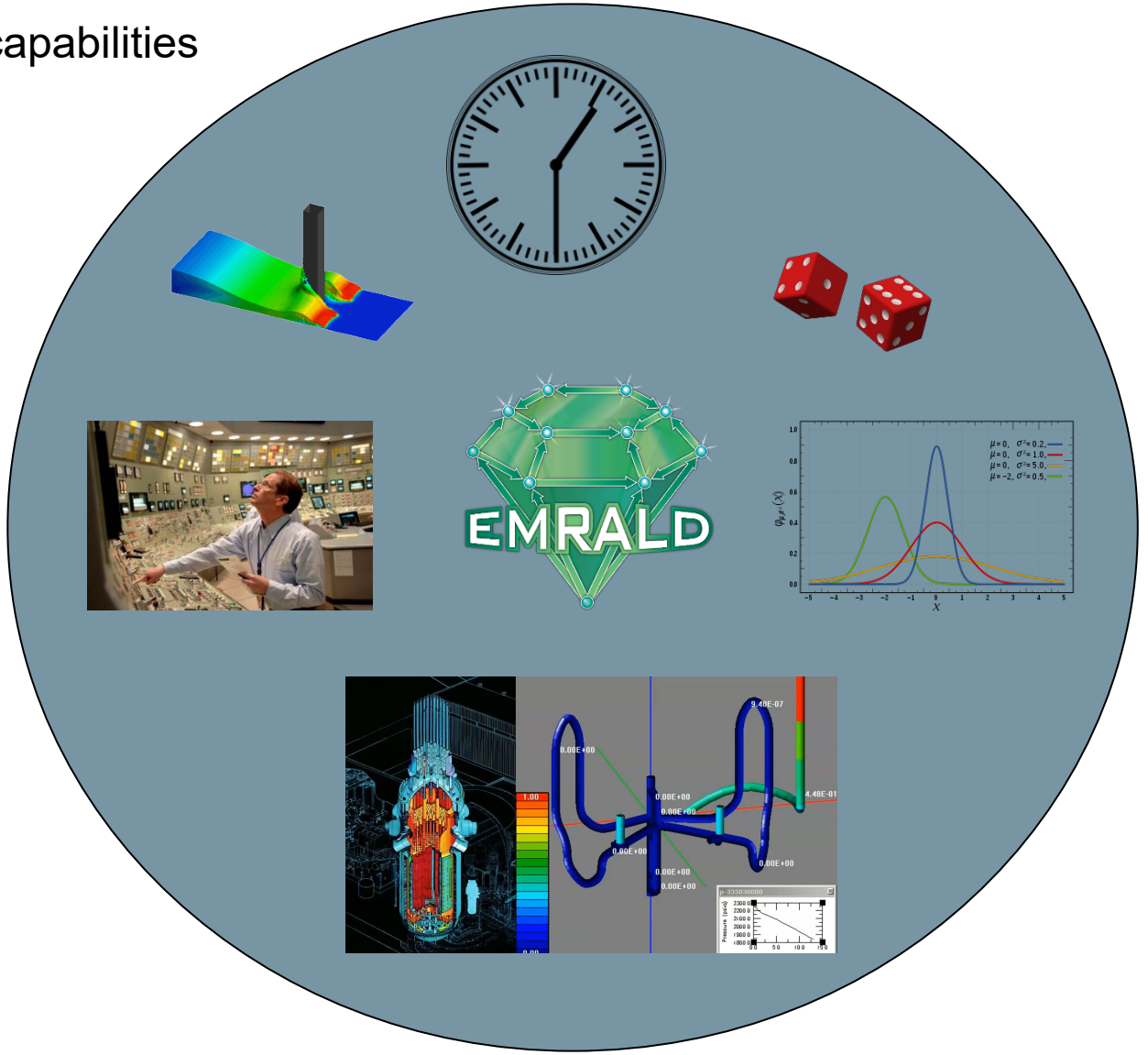


Why EMRALD (cont.)

3. Couple existing physics tools with Dynamic PRA capabilities
4. Analyze time dependent conditions
5. Conditionally adjust failure rates





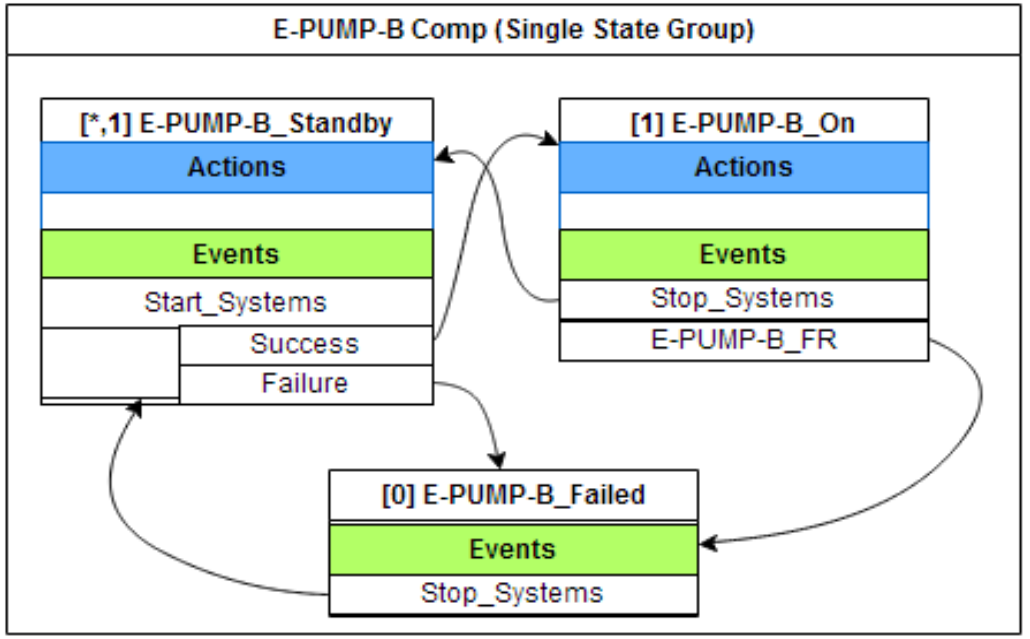


EMRALD Modeling

States

- Actions (transition, change variables, run script)
- Events -> Action (sampling, conditions, time, etc.)

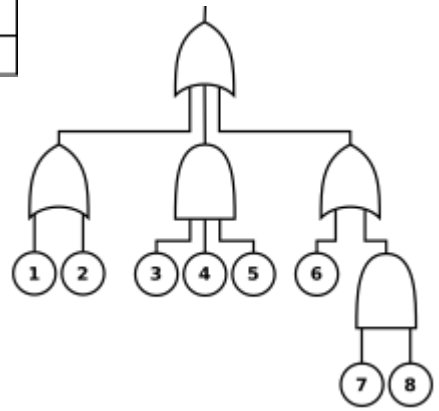
State
Actions
Transition
Change Variable
Run Script
Events
Failure Rate Sampling
Timer
State Change
Logic Tree
Evaluate Variable
External Event



Diagrams

- Components
- Systems
- Plant response

Logic Trees



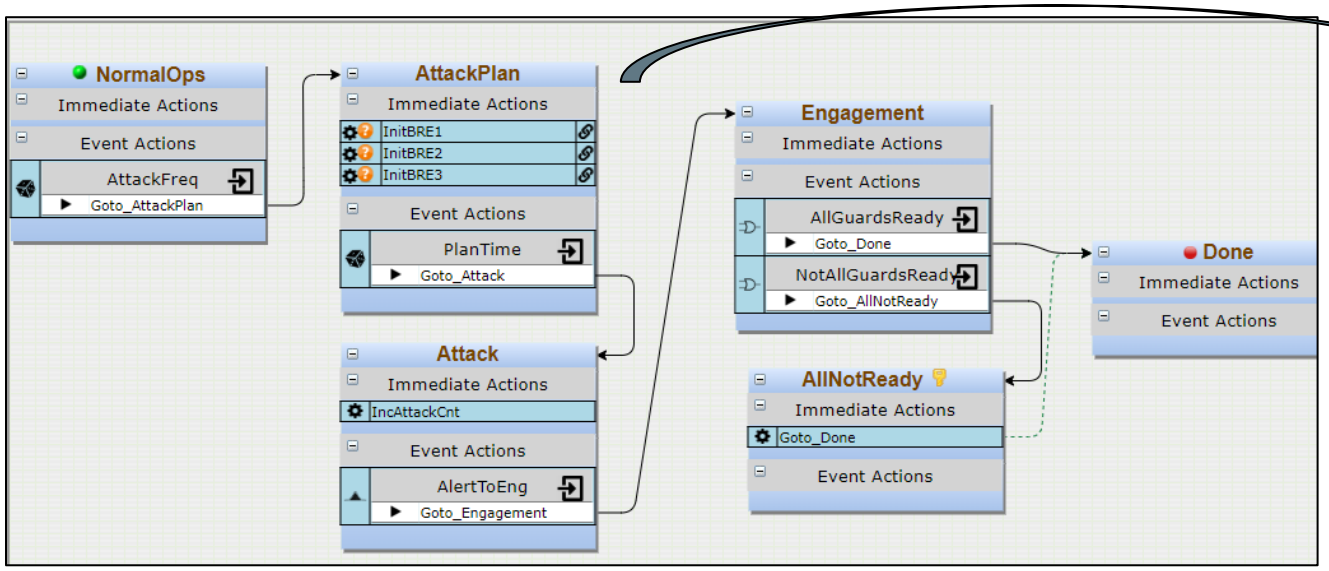
Variables

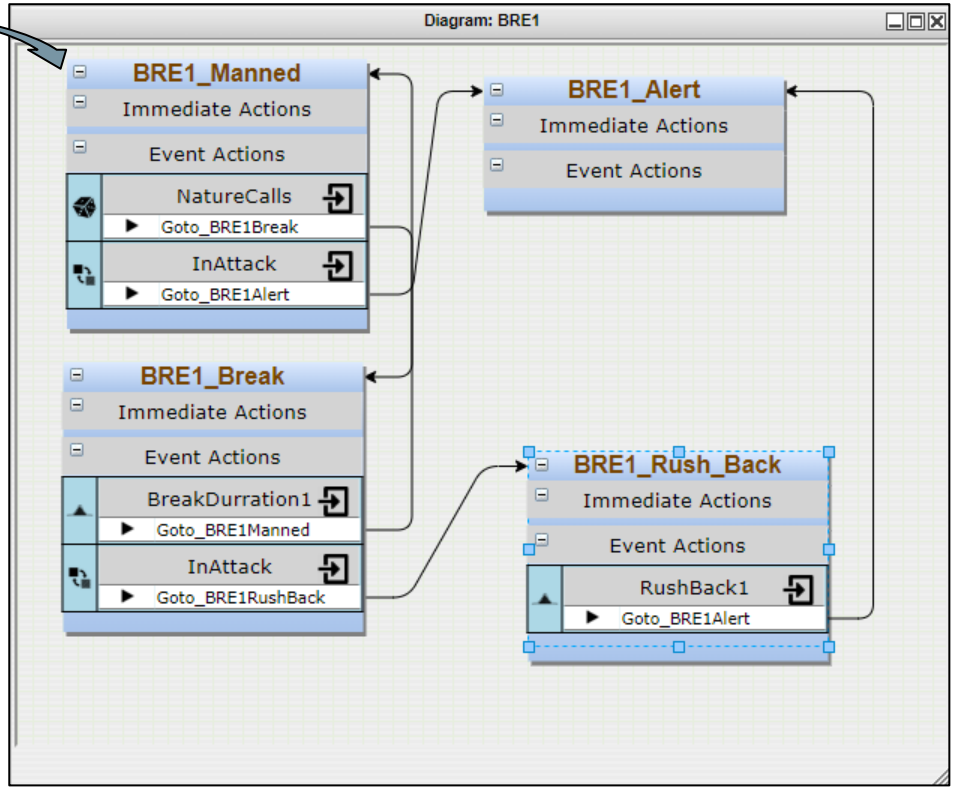
External Links

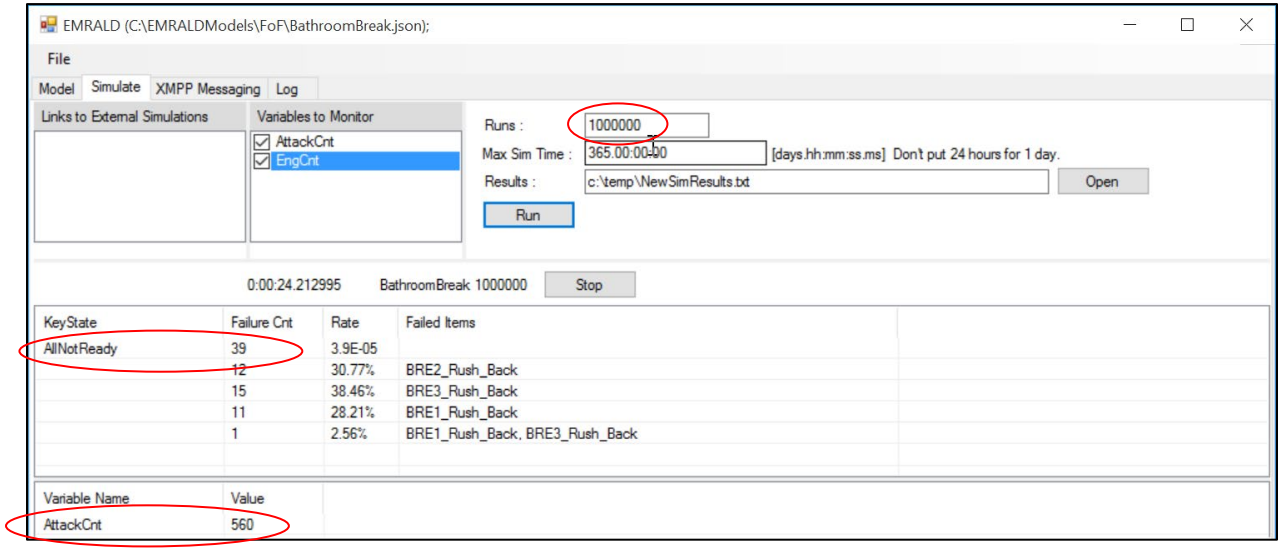
Use Case Study 1 : Bathroom Breaks

What risk increase is there for an attack scenario if guards are allowed to take random and unobservable Bathroom breaks from BREs without a relief requirement?

EMRALD Model: Bathroom Break







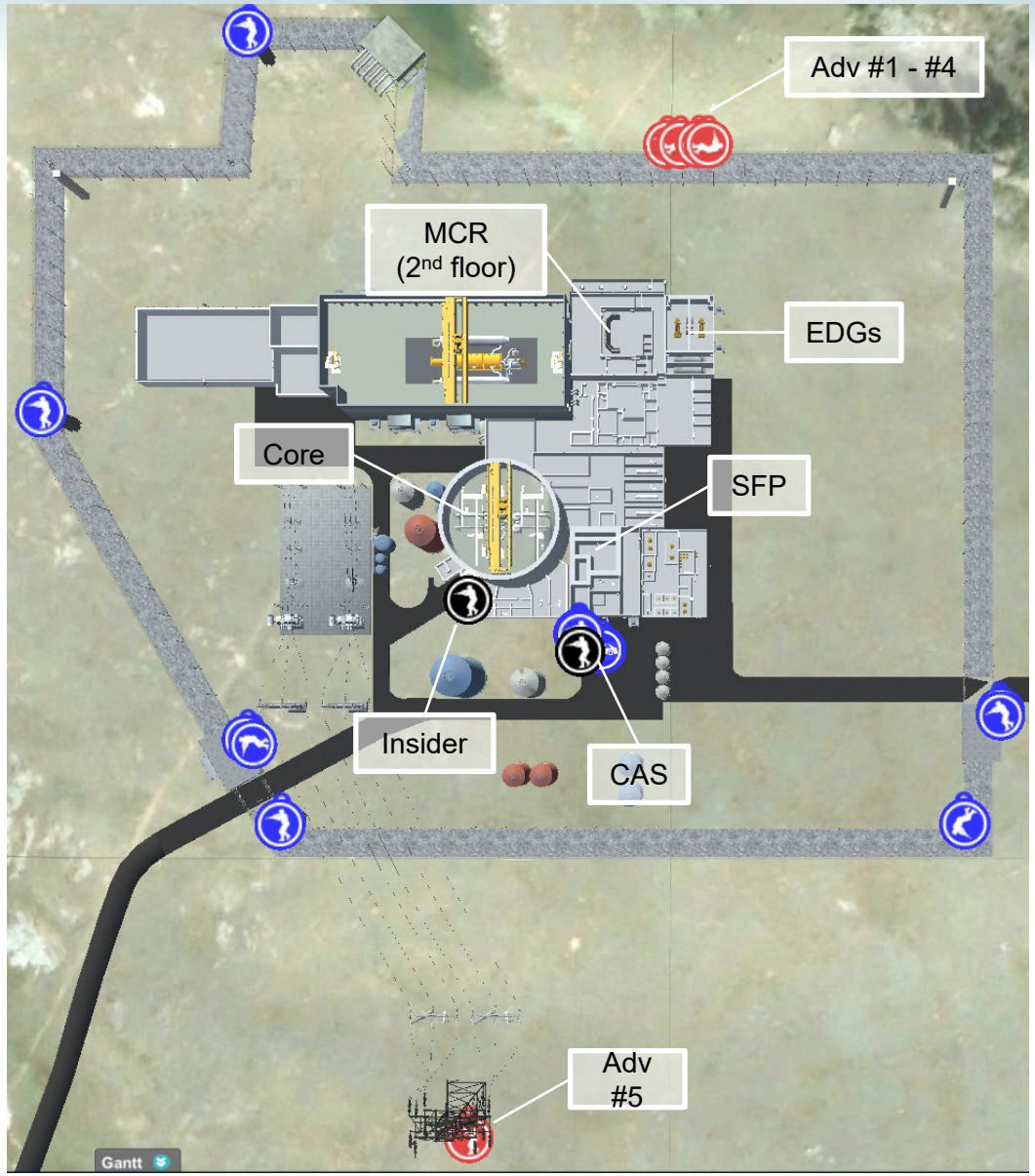
1E6 simulations → 560 attacks → 39 times (7%) guards not ready

Case Study 2: Static vs Dynamic FoF

Attack Scenario:

- Insider (technician) does maintenance on TDPs
- Adv #5 attacks transmission tower
- Adv #1 - #4 attack 2/2 EDGs

Step	Action	Purpose	Action time (seconds)
1	Adv-5 places explosive charges on the legs to the main power line towers and waits for the detonation cue.	Isolate LPNPP from offsite power	200
2	Adv-1, 2, 3 & 4 sneak on foot to the north-side of the facility.	Evade detection by tower guards	300
3	Adv-3 cuts a hole in the outer fence.	Infiltrate the protected area	20
4	Adv-3 enters PIDAS and heads to the inner fence followed by Adv-1,2,4.		5
5	Adv-3 cuts a hole in the inner fence.		20
6	Adv-1,2,3,4 enter the protected area and go towards the generator room.		10
7	Adv-3 unlocks the door to generator room.	Infiltrate the generator room	20
8	Team-1 (i.e. Adv-1 and 2) go to Emergency Diesel Generator (EDG) A and Team-2 (i.e. Adv-3 and 4) go to EDG B.	Destroy EDGs	20
9	Team-1 set-up explosives at EDG A while Team-2 set-up at EDG B.		40
10	Team-1 detonate EDG A and Team-2 detonate EDG B.		0
11	Adv-5 detonates main power line upon hearing explosions or gunfights inside LPNPP.	Create an SBO event	0



Static Analysis with DEPO

Step	Action	Purpose	Action time (seconds)
1	Adv-5 places explosive charges on the legs to the main power line towers and waits for the detonation cue.	Isolate LPNPP from offsite power	200
2	Adv-1, 2, 3 & 4 sneak on foot to the north-side of the facility.	Evade detection by tower guards	300
3	Adv-3 cuts a hole in the outer fence.	Infiltrate the protected area	20
4	Adv-3 enters PIDAS and heads to the inner fence followed by Adv-1,2,4.		5
5	Adv-3 cuts a hole in the inner fence.		20
6	Adv-1,2,3,4 enter the protected area and go towards the generator room.		10
7	Adv-3 unlocks the door to generator room.	Infiltrate the generator room	20
8	Team-1 (i.e. Adv-1 and 2) go to Emergency Diesel Generator (EDG) A and Team-2 (i.e. Adv-3 and 4) go to EDG B.	Destroy EDGs	20
9	Team-1 set-up explosives at EDG A while Team-2 set-up at EDG B.		40
10	Team-1 detonate EDG A and Team-2 detonate EDG B.		0
11	Adv-5 detonates main power line upon hearing explosions or gunfights inside LPNPP.	Create an SBO event	0

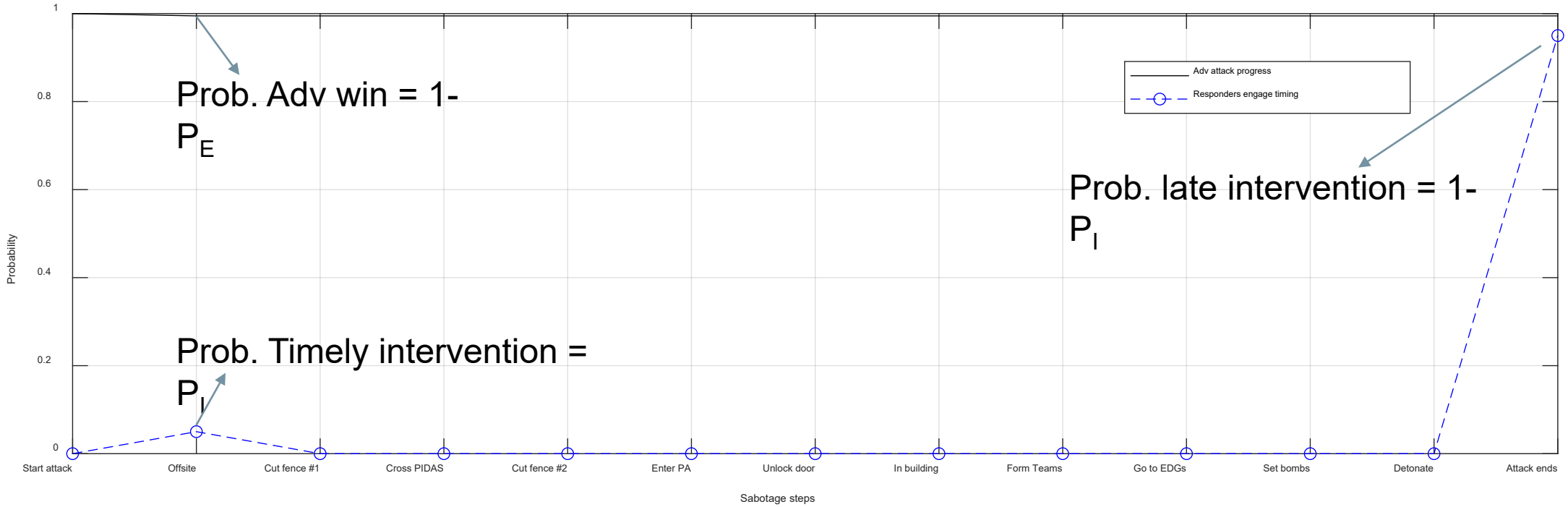
CDP

Assessment & comm time

Response Force prep. time

- P_I = Prob. detection up to CDP = 0.05
- $P_N = U_{i=1}^{4} P_{i-th\ Adv\ neutralized}$
  - P_N for 1 Adv = 1-(1-P_{SPO})*(1-P_{RF}) = 0.5707
  - P_N all Advs = $(0.5707)^4$ = 0.1061
- $P_E = P_I * P_N$ = **5.3E-3**
- Sabotage outcome:
  - P(LOOP, 2 EDGs, no TDPs) = P_E = 5.3E-3
  - P(SBO, no TDPs) = 1-P_E = 0.9947

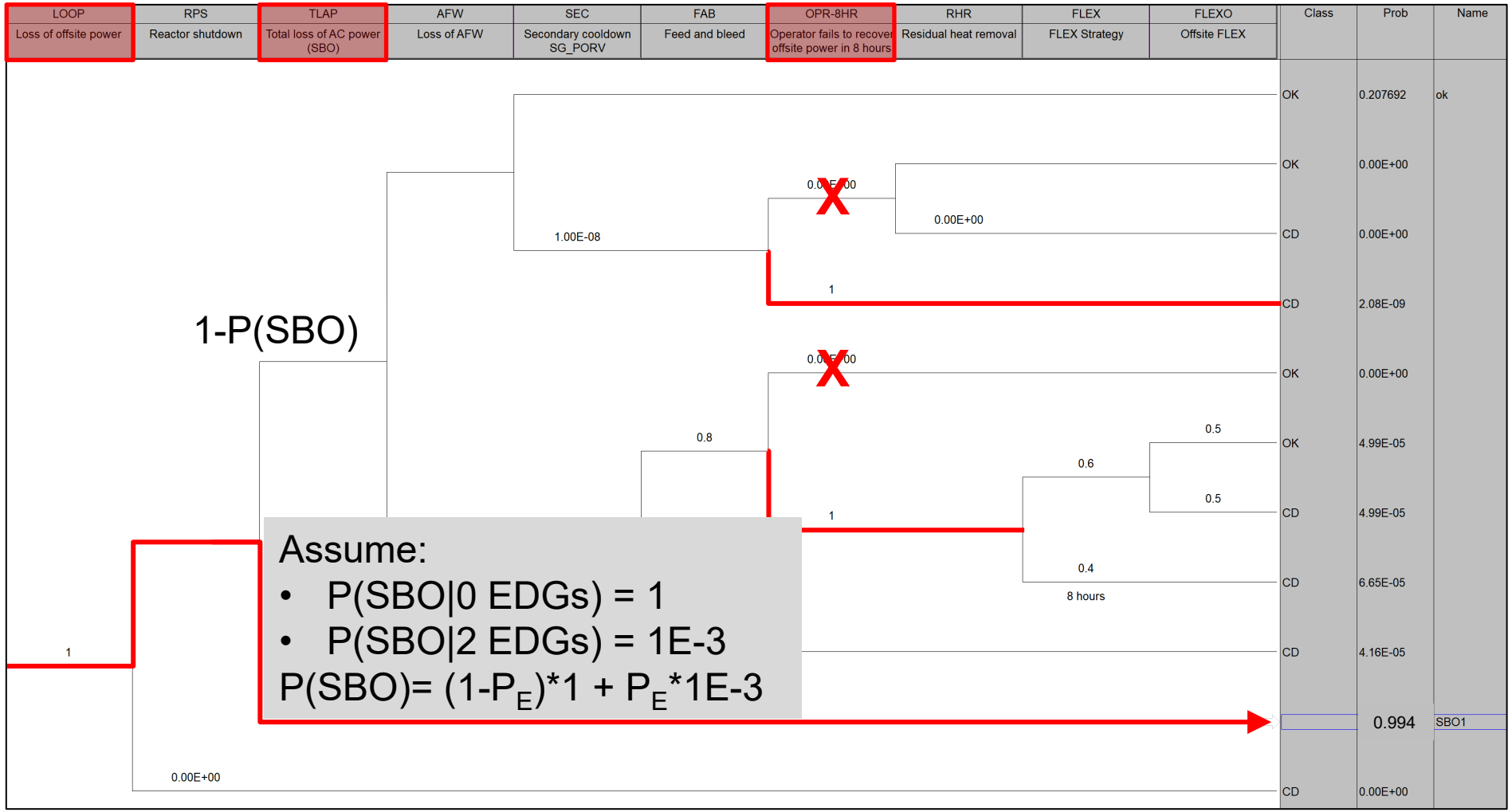
Timing Chart with Static DEPO



- Sabotage outcome:
  - P(LOOP, 2 EDGs, no TDPs) = 5.3E-3
  - P(SBO, no TDPs) = 0.9947

LOOP ET

Adv #5 Adv #1 - #4 Adv #5



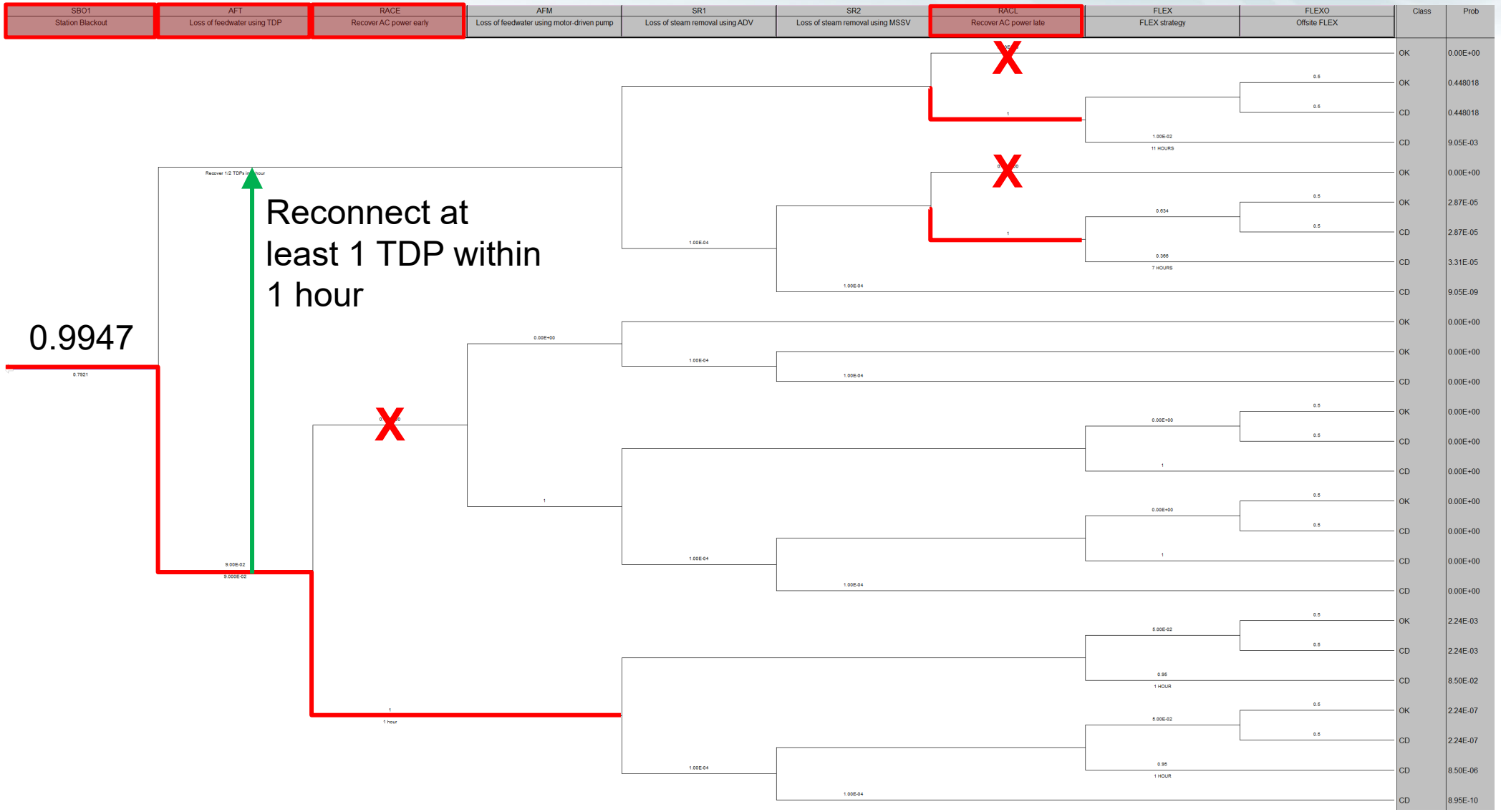
Actions to prevent LOOP:

1. Secondary heat removal with AFW
2. Primary heat removal with F&B sustained by FLEX generator

ET taken from: INL, “INL/EXT-16-40055: Multi-hazard advanced seismic probabilistic assessment tools and applications”, 2016

SBO ET

Adv #1 - #4 | Insider | Adv #5 | Adv #5



Actions to prevent SBO:

1. Remove heat using TDP & sustain steam regulation using FLEX generator
2. Remove heat using FLEX pump & generator

Ref: INL, “INL/EXT-18-51531: Risk and cost analysis of utilizing FLEX equipment for O&M cost reduction in nuclear power plants”, 2018

Dynamic Analysis with EMRALD

Step	Action	Purpose	Action time (seconds)
1	Adv-5 places explosive charges on the legs to the main power line towers and waits for the detonation cue.	Isolate LPNPP from offsite power	200
2	Adv-1, 2, 3 & 4 sneak on foot to the north-side of the facility.	Evade detection by tower guards	N(300,30)
3	Adv-3 cuts a hole in the outer fence.	Infiltrate the protected area	N(20,2)
4	Adv-3 enters PIDAS and heads to the inner fence followed by Adv-1,2,4.		N(5,0.5)
5	Adv-3 cuts a hole in the inner fence.		N(20,2)
6	Adv-1,2,3,4 enter the protected area and go towards the generator room.		N(10,1)
7	Adv-3 unlocks the door to generator room.	Infiltrate the generator room	N(20,2)
8	Team-1 (i.e. Adv-1 and 2) go to Emergency Diesel Generator (EDG) A and Team-2 (i.e. Adv-3 and 4) go to EDG B.	Destroy EDGs	N(20,2)
9	Team-1 set-up explosives at EDG A while Team-2 set-up at EDG B.		N(40,4)
10	Team-1 detonate EDG A and Team-2 detonate EDG B.		0
11	Adv-5 detonates main power line upon hearing explosions or gunfights inside LPNPP.	Create an SBO event	0

Dynamic scenario assumptions:

- If SPO engages Adv while still in range, Adv is delayed
- If an Adv team member is shot, his teammate is delayed
- [If alarm is triggered, EDG room is filled with smoke upon entry when the smoke generator does not fail due to random failures]

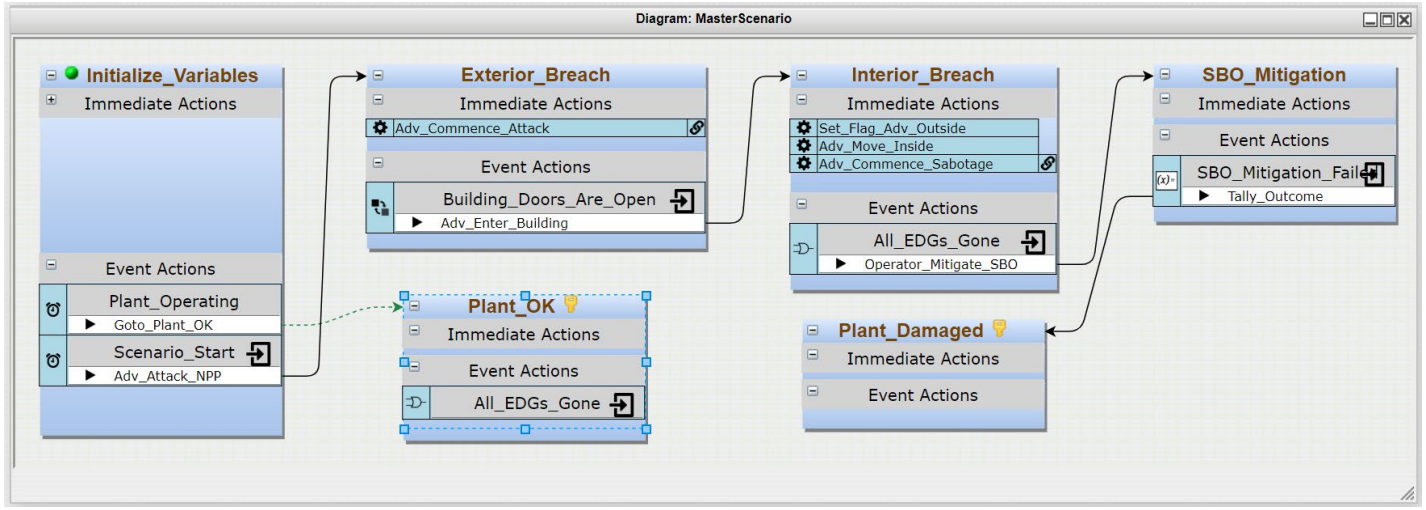
If Adv is delayed sufficiently, RF may arrive in time

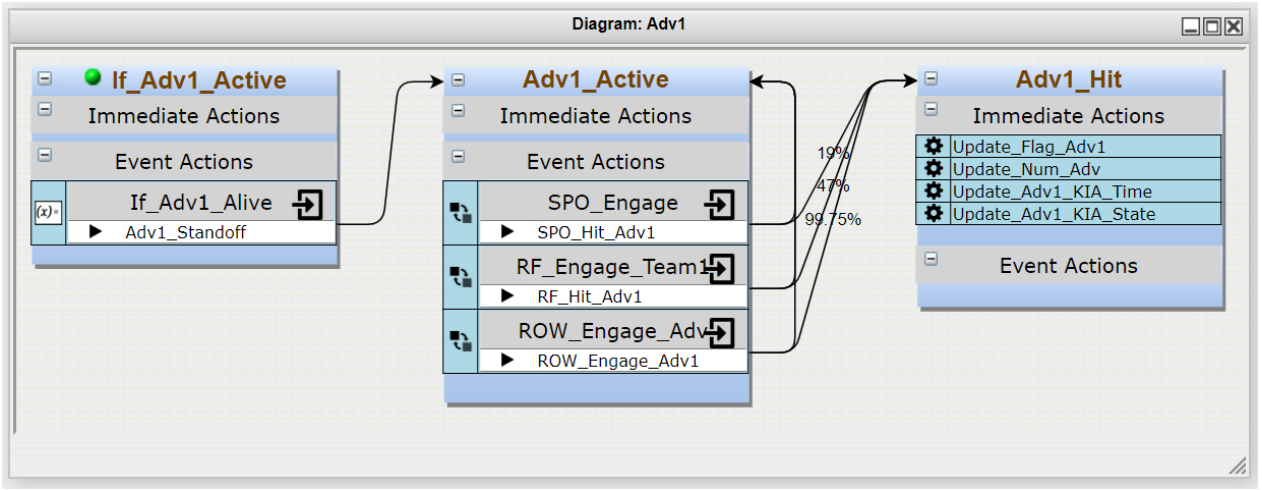
If Adv is detected here, SPO may respond in time

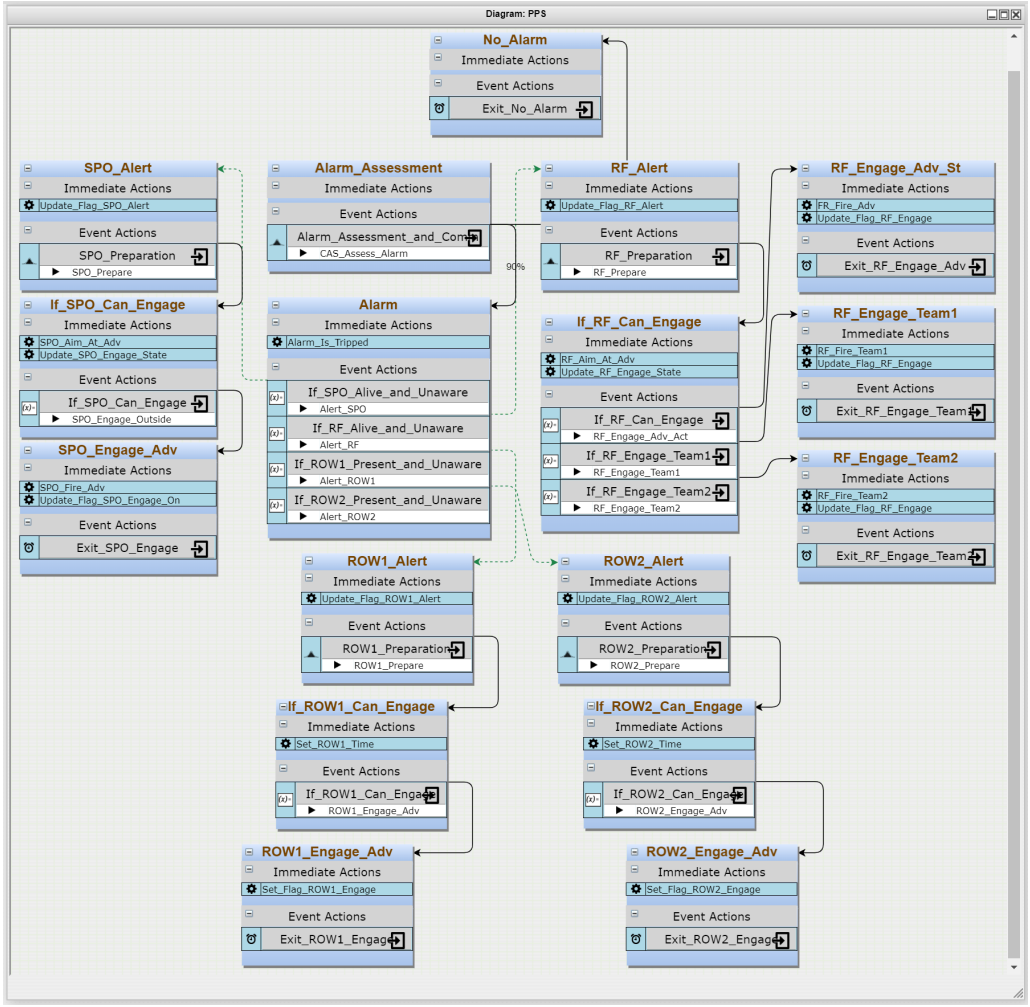
Adv out of SPO's range

<u>Future effort</u>: Using dynamic HRA to estimate the scenario's dynamics

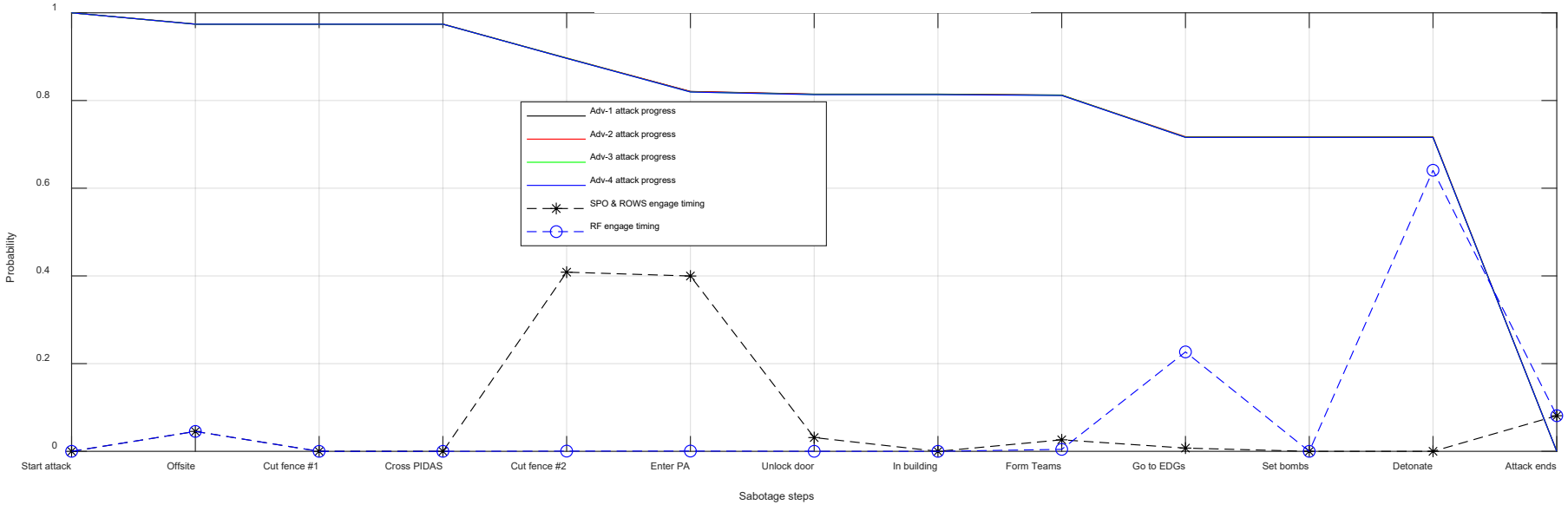
EMRALD Model

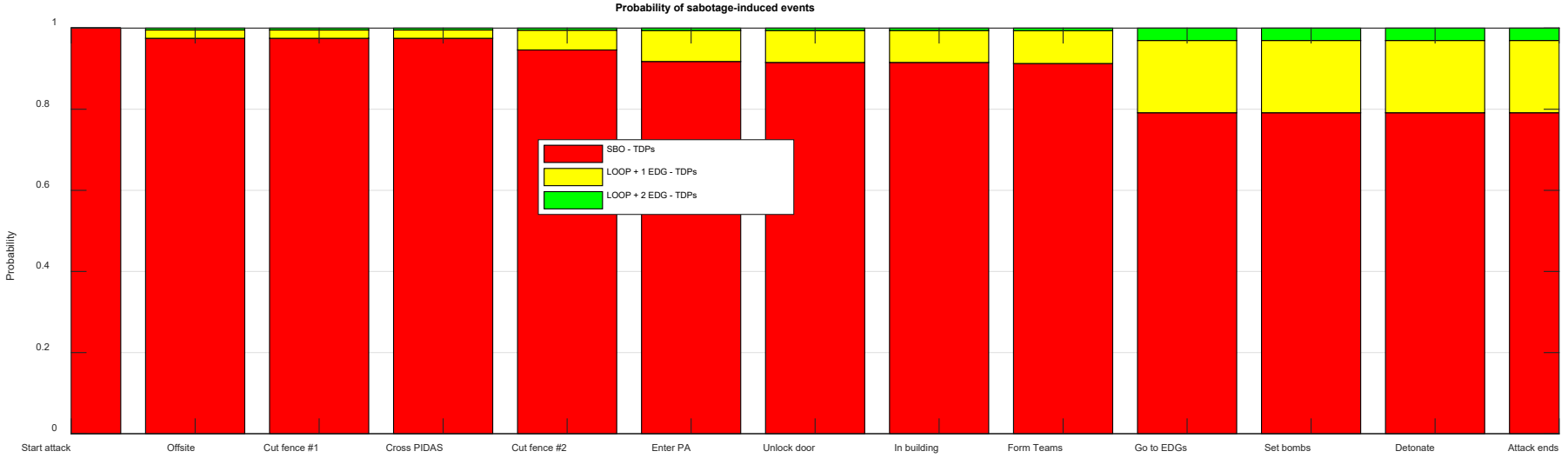






Event timeline and probabilities





0.79

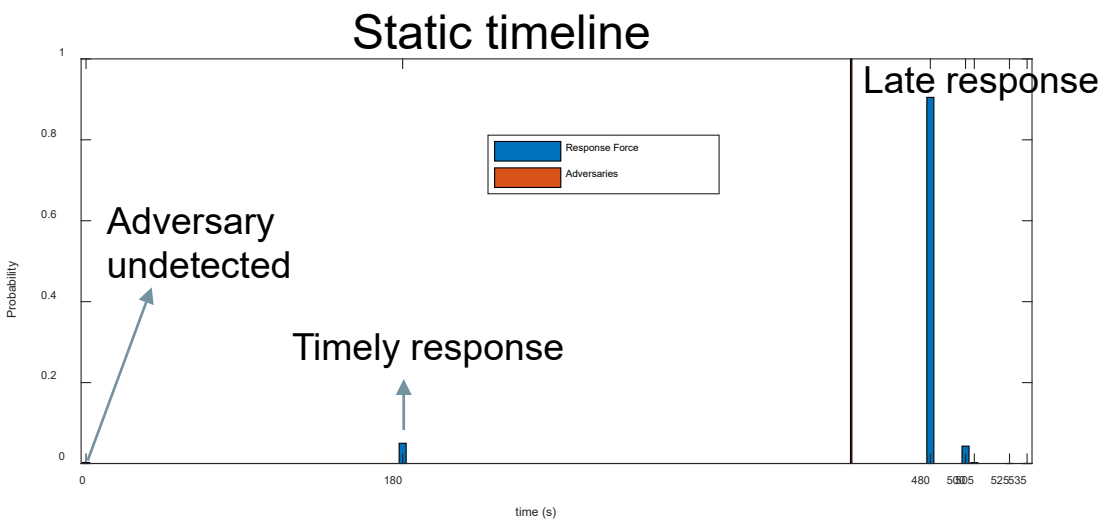
Suppression of adversaries

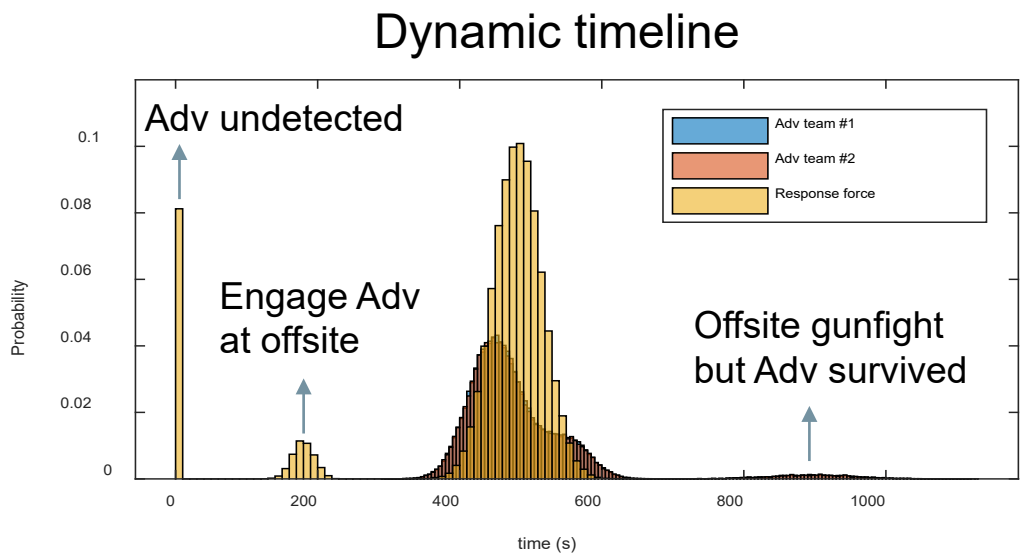
Probable sabotage outcome

Risk of sabotage outcome

Results

	Static (DEPO)	(Dynamic) EMRALD
Sabotage events	SBO without TDPs, P=0.9947 LOOP without TDPs, P=5.3E-3	SBO without TDPs, P=0.79 LOOP without TDPs and 1 EDG, P=0.18 LOOP without TDPs, P=3E-2
CCDP from plant PRA	5.4E-1	4.3E-1



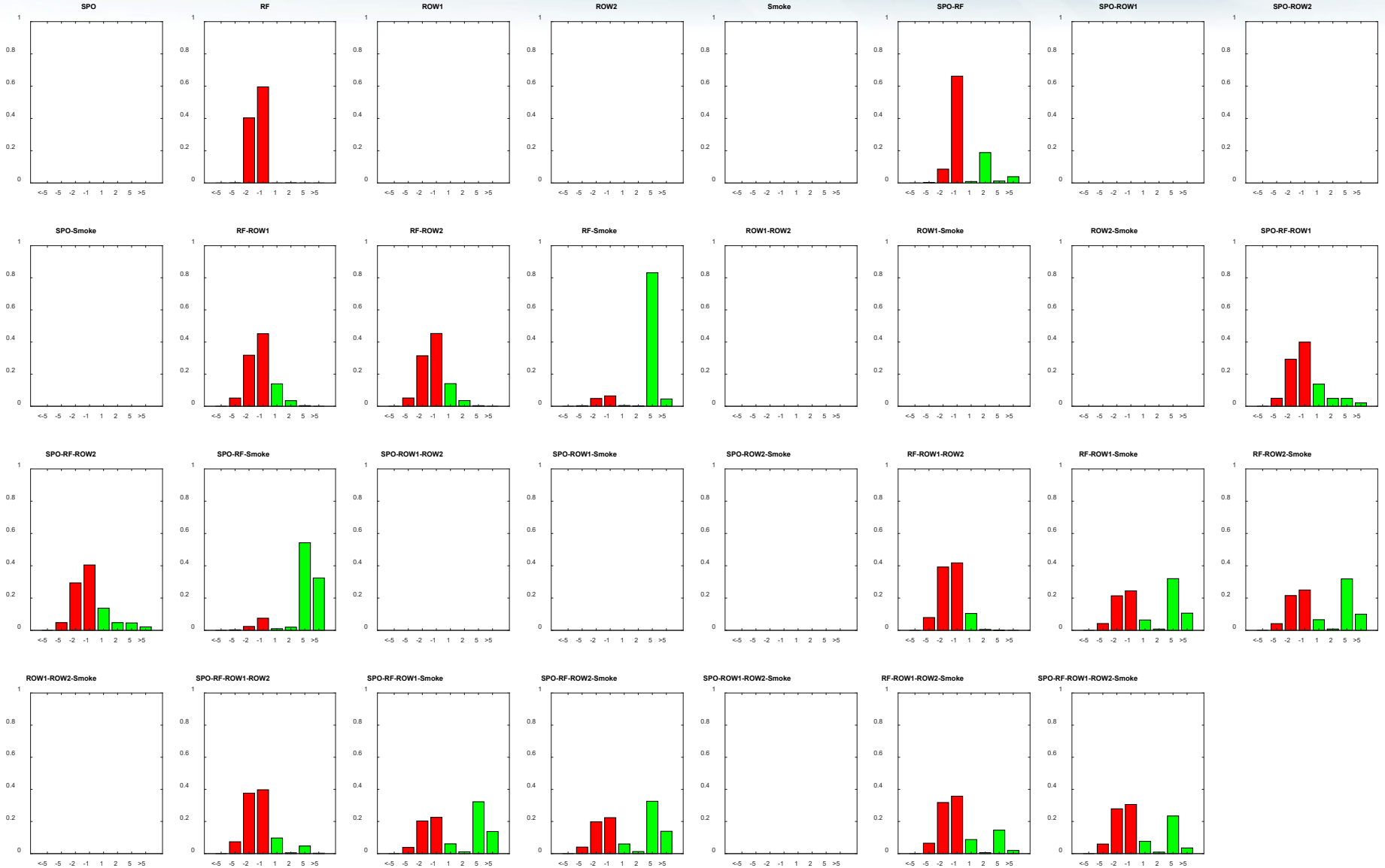


Case Study 3: Phys. Prot. Design Comparison

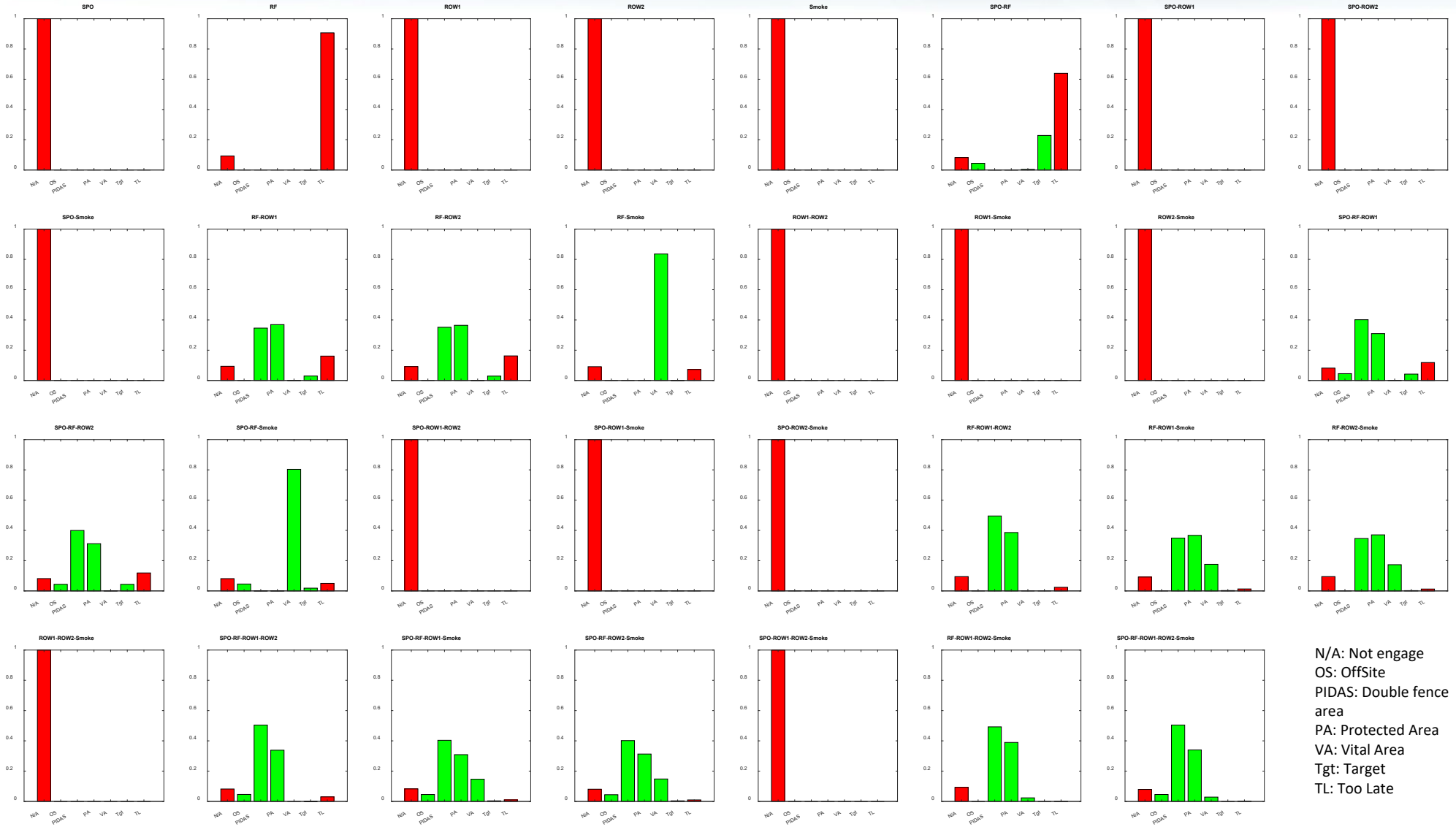
- Enumerate combinations of these elements in EMRALD:
  - SPO guards
  - Mobile tactical Response Force (RF)
  - Smoke generator as an indoor delay element
  - A pair of Remote Operated Weapon Systems (ROWS)

  Total 2^4-1 = 31 combinations

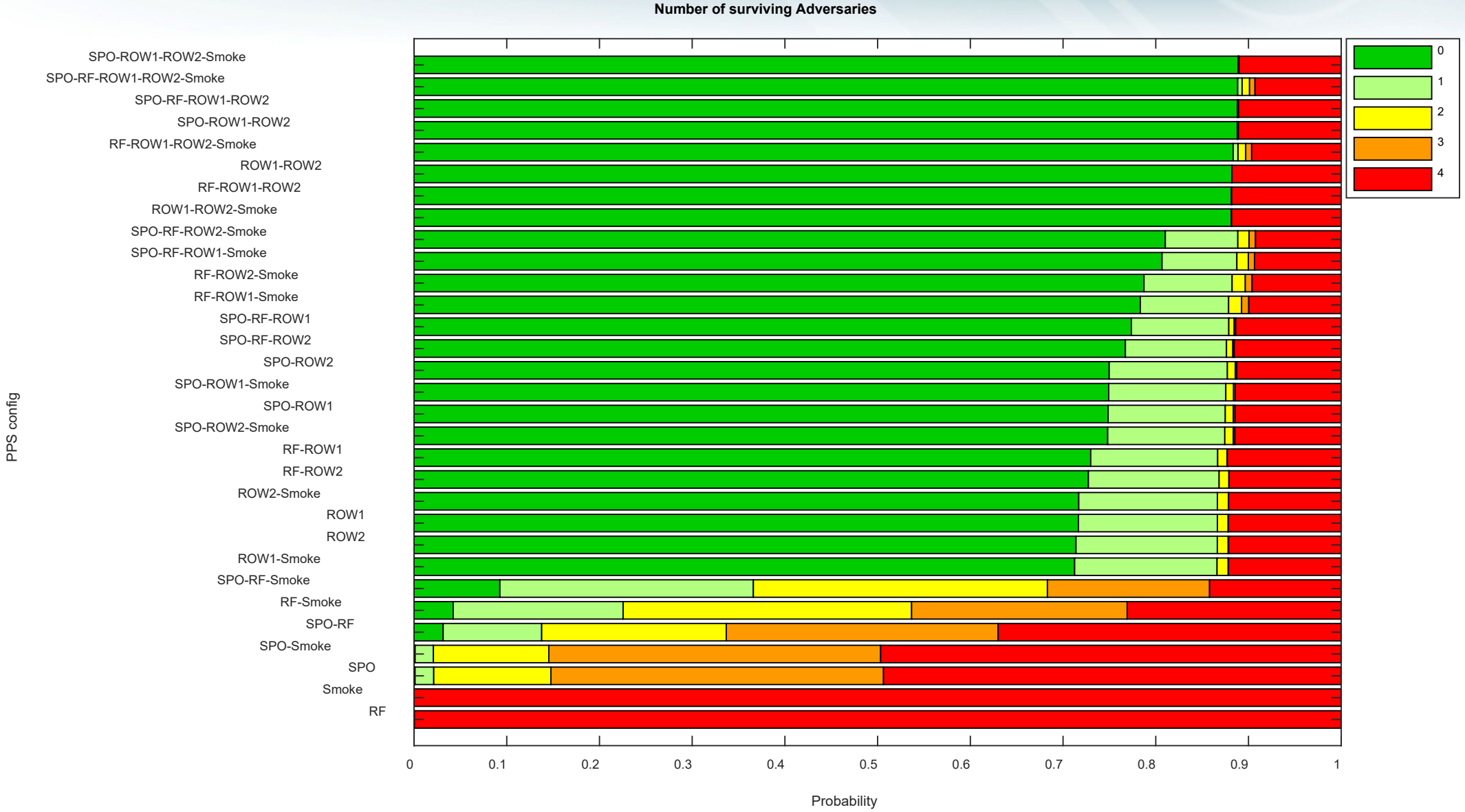
Timing of Response Force arrival BEFORE sabotage is completed (in minutes)

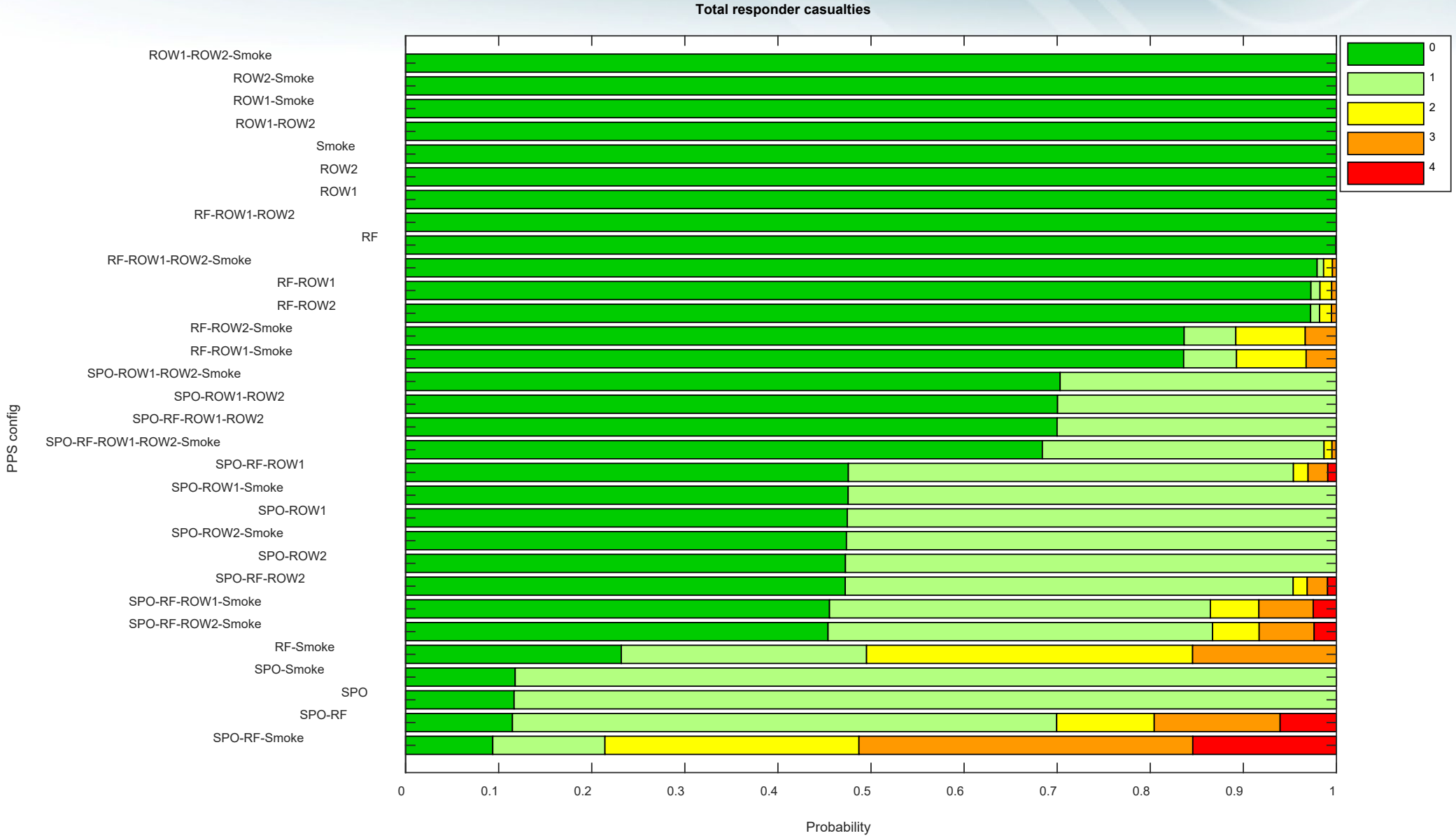


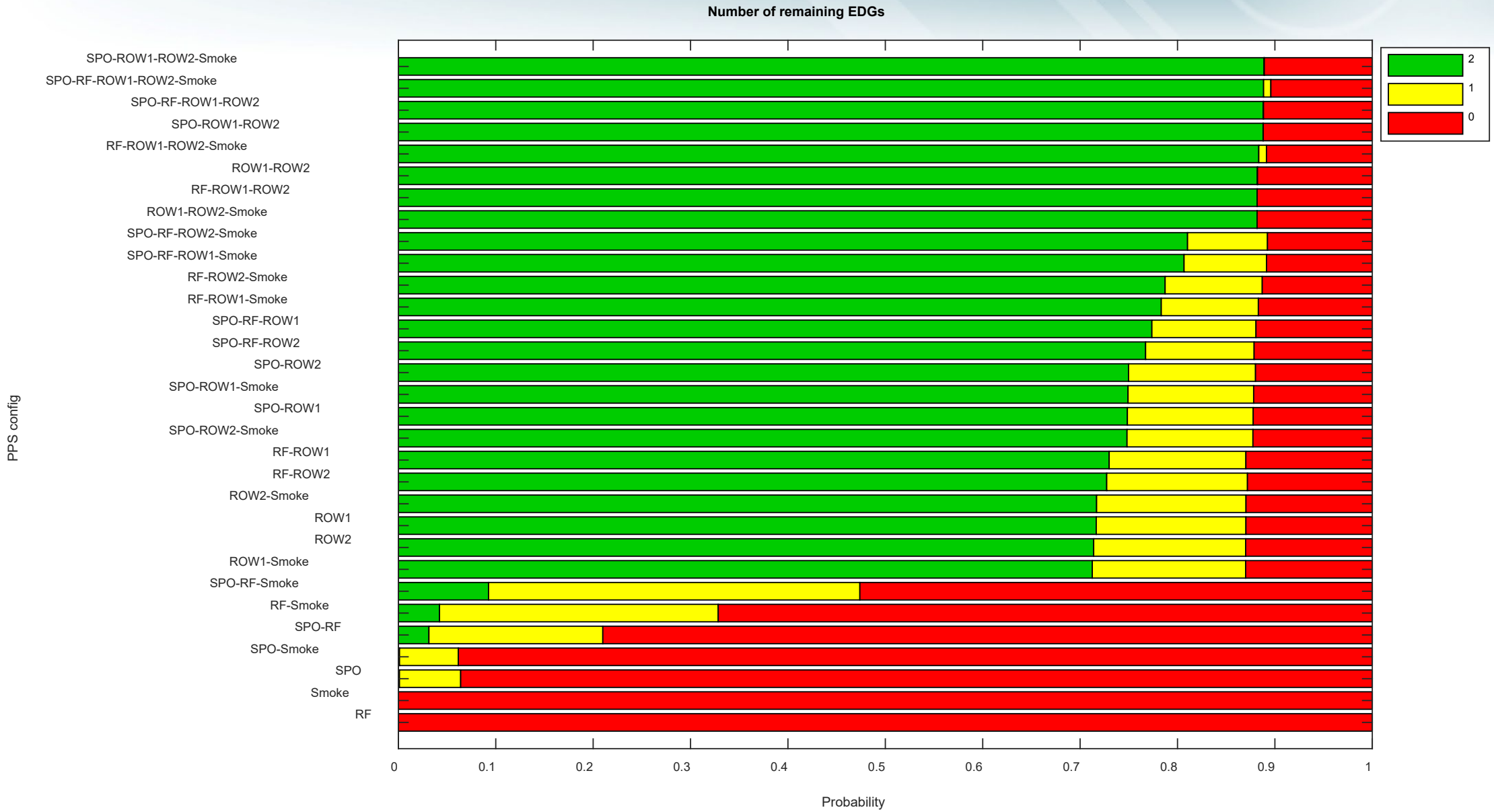
Physical areas where Response Force engage Adversary



N/A: Not engage
OS: OffSite
PIDAS: Double fence area
PA: Protected Area
VA: Vital Area
Tgt: Target
TL: Too Late


Number of surviving Adversaries
SPO-ROW1-ROW2-Smoke
SPO-RF-ROW1-ROW2-Smoke
SPO-RF-ROW1-ROW2
SPO-ROW1-ROW2
RF-ROW1-ROW2-Smoke
ROW1-ROW2
RF-ROW1-ROW2
ROW1-ROW2-Smoke
SPO-RF-ROW2-Smoke
SPO-RF-ROW1-Smoke
RF-ROW2-Smoke
RF-ROW1-Smoke
SPO-RF-ROW1
SPO-RF-ROW2
SPO-ROW2
SPO-ROW1-Smoke
SPO-ROW1
SPO-ROW2-Smoke
RF-ROW1
RF-ROW2
ROW2-Smoke
ROW1
ROW2
ROW1-Smoke
SPO-RF-Smoke
RF-Smoke
SPO-RF
SPO-Smoke
SPO
Smoke
RF
PPS config
0
1
2
3
4
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Probability


Total responder casualties
ROW1-ROW2-Smoke
ROW2-Smoke
ROW1-Smoke
ROW1-ROW2
Smoke
ROW2
ROW1
RF-ROW1-ROW2
RF
RF-ROW1-ROW2-Smoke
RF-ROW1
RF-ROW2
RF-ROW2-Smoke
RF-ROW1-Smoke
SPO-ROW1-ROW2-Smoke
SPO-ROW1-ROW2
SPO-RF-ROW1-ROW2
SPO-RF-ROW1-ROW2-Smoke
SPO-RF-ROW1
SPO-ROW1-Smoke
SPO-ROW1
SPO-ROW2-Smoke
SPO-ROW2
SPO-RF-ROW2
SPO-RF-ROW1-Smoke
SPO-RF-ROW2-Smoke
RF-Smoke
SPO-Smoke
SPO
SPO-RF
SPO-RF-Smoke
PPS config
0
1
2
3
4
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Probability


Number of remaining EDGs
SPO-ROW1-ROW2-Smoke
SPO-RF-ROW1-ROW2-Smoke
SPO-RF-ROW1-ROW2
SPO-ROW1-ROW2
RF-ROW1-ROW2-Smoke
ROW1-ROW2
RF-ROW1-ROW2
ROW1-ROW2-Smoke
SPO-RF-ROW2-Smoke
SPO-RF-ROW1-Smoke
RF-ROW2-Smoke
RF-ROW1-Smoke
SPO-RF-ROW1
SPO-RF-ROW2
SPO-ROW2
SPO-ROW1-Smoke
SPO-ROW1
SPO-ROW2-Smoke
RF-ROW1
RF-ROW2
ROW2-Smoke
ROW1
ROW2
ROW1-Smoke
SPO-RF-Smoke
RF-Smoke
SPO-RF
SPO-Smoke
SPO
Smoke
RF
PPS config
2
1
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Probability


Performance Comparison
SPO-RF-ROW1-ROW2-Smoke
SPO-ROW1-ROW2-Smoke
SPO-RF-ROW1-ROW2
SPO-ROW1-ROW2
RF-ROW1-ROW2-Smoke
ROW1-ROW2
RF-ROW1-ROW2
ROW1-ROW2-Smoke
SPO-RF-ROW2-Smoke
SPO-RF-ROW1-Smoke
RF-ROW2-Smoke
RF-ROW1-Smoke
SPO-RF-ROW1
SPO-RF-ROW2
SPO-ROW2
SPO-ROW1-Smoke
SPO-ROW1
SPO-ROW2-Smoke
RF-ROW1
RF-ROW2
ROW2-Smoke
ROW1
ROW2
ROW1-Smoke
SPO-RF-Smoke
RF-Smoke
SPO-RF
SPO
SPO-Smoke
RF
Smoke
PPS config
Target Set Protection
Cost
1
0
1
Normalized Metric

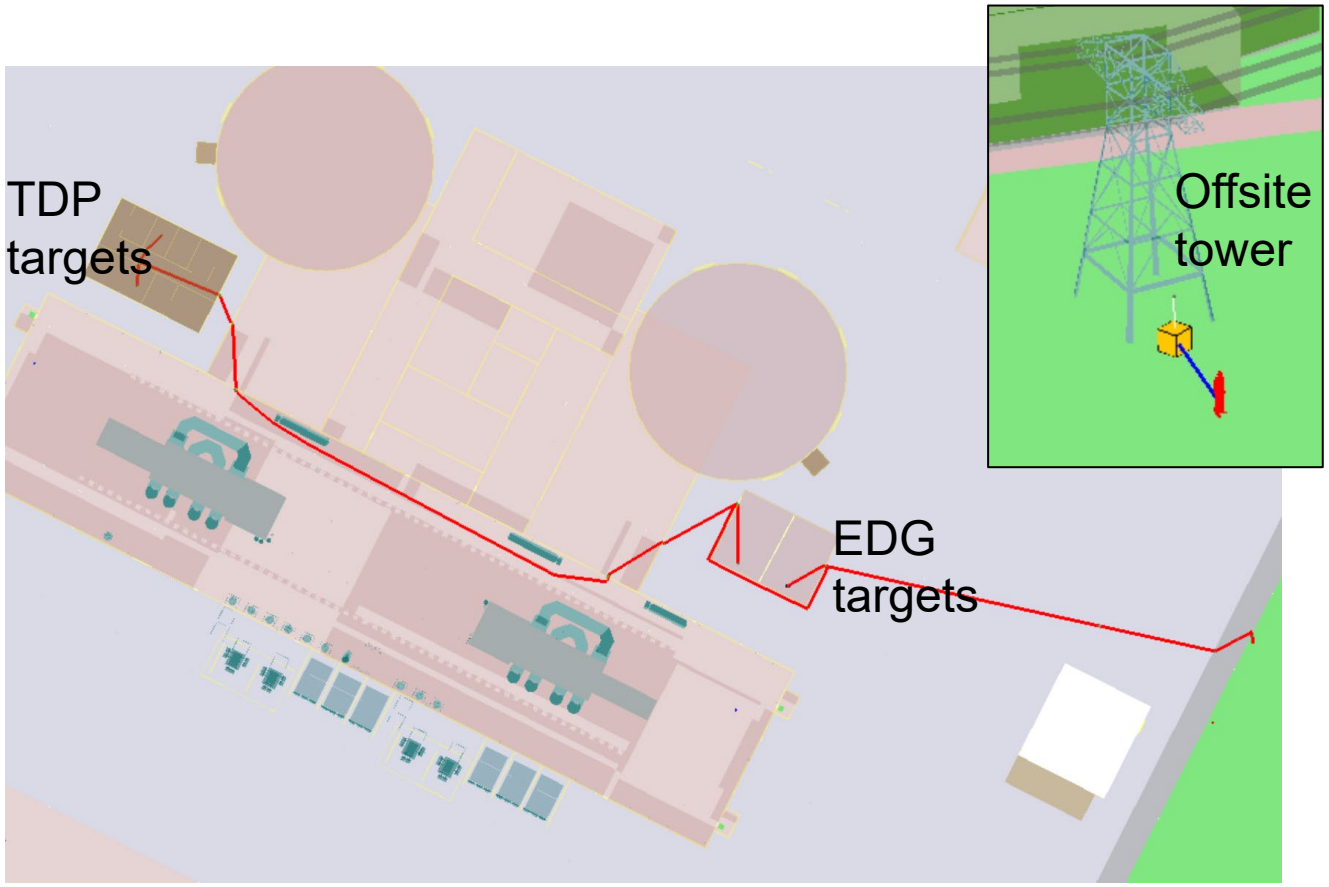
Case Study 4: Crediting Backup Safety Equipment

Diverse and Flexible Mitigation Strategy (FLEX)

Sabotage Scenario Using Hypothetical Plant

Scenario:
Damage NPP by sabotaging its power line, EDGs and TDPs

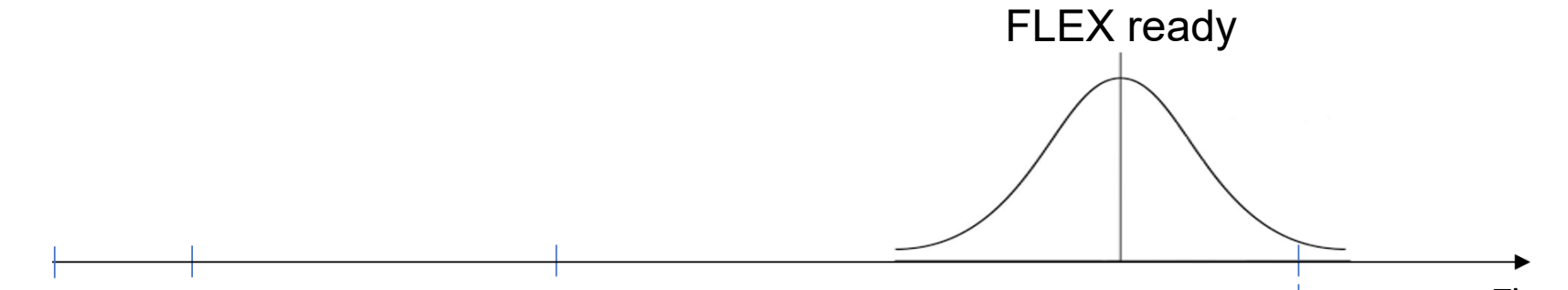
Station Blackout	AFW Using TDP	Recover Offsite Power (Early)	AFW Using MDP	Steam Removal Using MSADV	Steam Removal Using MSSV	Recover Offsite Power (Late)	NO	SP[1)]
SBO	AFT	RACE	AFM	SHR1	SHR2	RACL		
						9.61E-1	1	9.31E-1
				9.723E-1		3.9E-2 (11 HR)	2	3.78E-2
	X					9.0E-1	3	2.484E-2
					9.99885E-1	1.0E-1 (7 HR)	4	2.76E-3
				2.77E-2	1.15E-4		5	3.173E-6
				9.96791E-1			6	1.386E-3
			9.991486E-1		9.990484E-1		7	4.458E-6
		X		3.209E-3	9.516E-4		8	4.246E-9
			8.514E-4				9	1.185E-6
		(1 HR)						CD in 1 hr



Possible Attack Outcomes

No.	System availability			Mitigation strategy
	Offsite power	EDG	TDP	
1	✓	✓	✓	N/A (Continue operation)
2	✓	✓	✗	Non-transient shutdown
3	✓	✗	✓	Non-transient shutdown
4	✓	✗	✗	Non-transient shutdown
5	✗	✓	✓	LOOP ET
6	✗	✓	✗	LOOP ET
7	✗	✗	✓	**FLEX** EDG strategy within 11 hours
8	✗	✗	✗	**FLEX** ELAP strategy within 1 hour

FoF-FLEX Timeline Model



FoF in AVERT

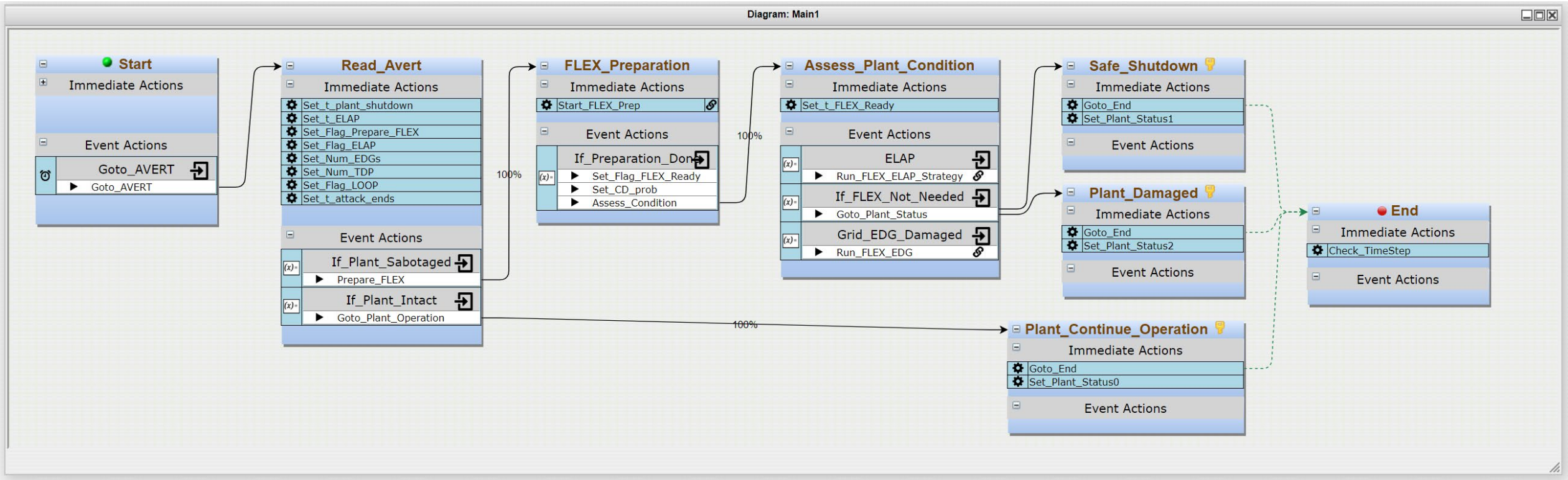
FLEX procedure in EMRALD

- No damage at all → **Plant continues operation**
- Retain DB safety systems → Mitigate using DB systems → **Safe Shutdown**
- Loss of several/all DB safety functions → FLEX ready. Run FLEX strategy based on assessment results → **Core Damage**

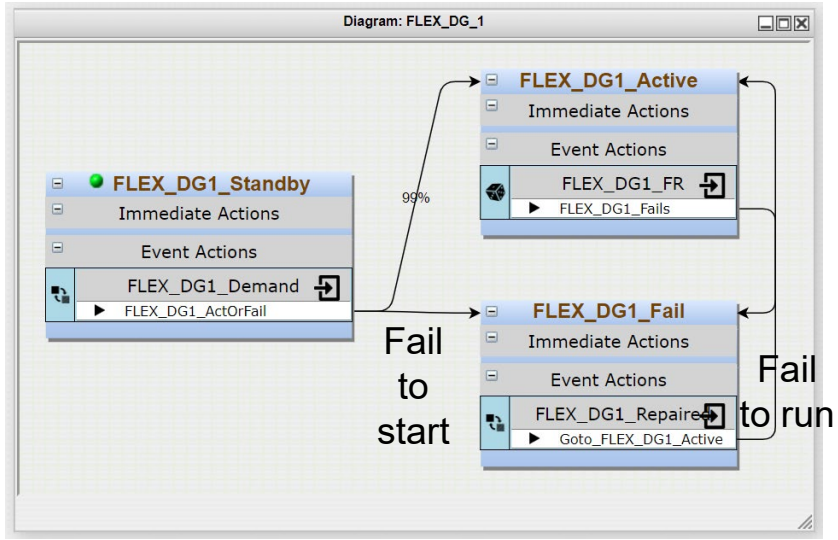
FLEX Procedure

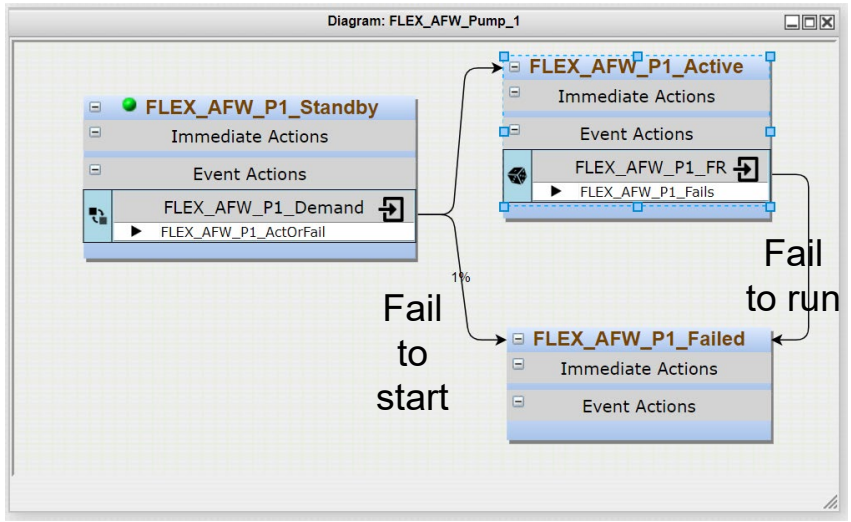
Number	Steps	Procedure	By	Notes
1	Open doors and get keys	FSG05		
2	Assess condition of plant sys & equipment	FSG05	MCR operator	Look for damage to equipment to determine FLEX strategy priority. See Addendum 5
3	Contact SAFER Control Center for ELAP event	FSG05	MCR operator	Phone call
4	Connect FLEX SG Makeup pumps' hose	FSG05	Dispatch maintenance	Addendum 1
5	Establish configuration to support FLEX 480V AC installation	FSG05	MCR operator Add2, and dispatch MCR operator Add17	Addendum 2 & 17
6	Connect FLEX Cables to 480V MCCs	FSG05	Dispatch O&M personnel	Addendum 9 & 12, 10,11,13
7	Open ALL breakers on MCCs	FSG05	Dispatch MCR Operator	
8	Conect FLEX RCS Makeup pump hoses	FSG05	Maintenance	Addendum 6 & 7
9	Inform Security of Security Area Access Breaches	FSG05	Dispatch MCR Operator	Addendum 15
10	Put a FLEX Diesel in service (1/2)	FSG19		
11	Restore Partial Lighting and Receptacle Power	FSG05		
12	Turn on supply breaker in FLEX DG enclosure	FSG05		
13	Evaluate potential usages for the portable equipment being delivered from RRC	FSG05		
14	Ensure support equipment - staged	FSG05		Addendum 4
15	Establish communication	FSG05		
	FLEX SG Makeup operation			
1	Valve operations to align FLEX pumps	FSG03	Operator (manual)	Addendum 1
2	Manual transfer switch	FSG03	Operator (manual)	

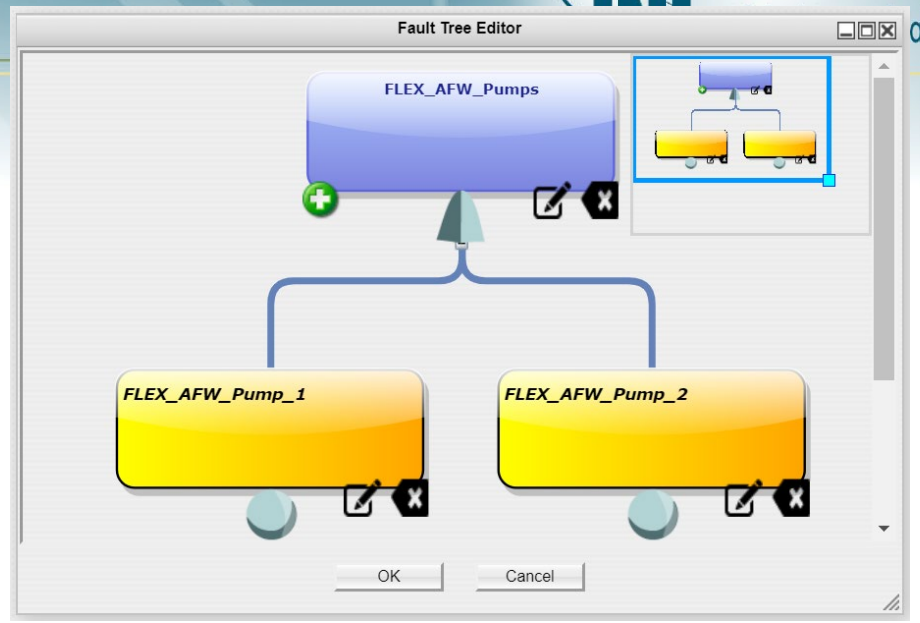
EMRALD Model

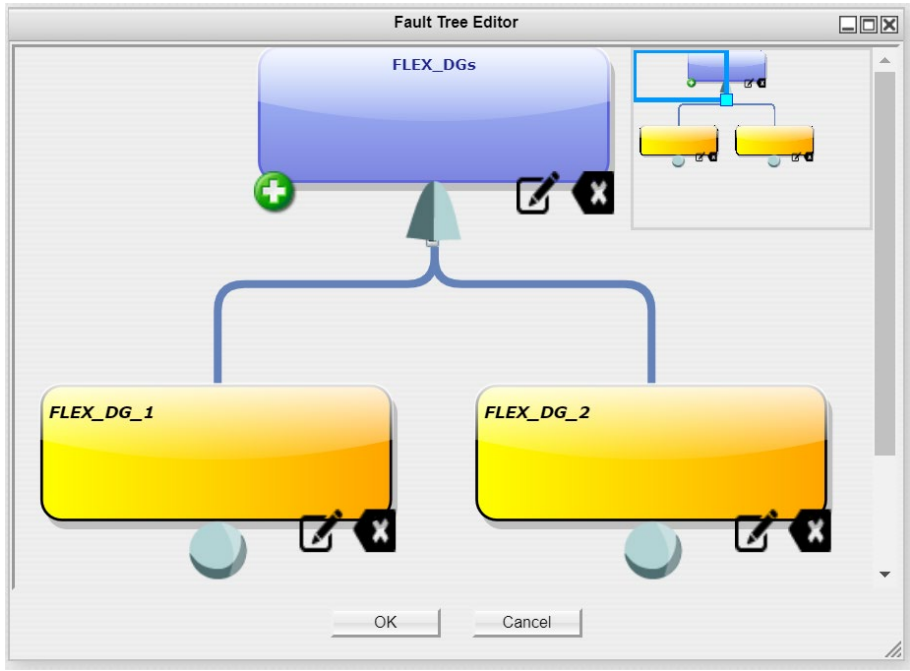


FLEX Equipment Failures

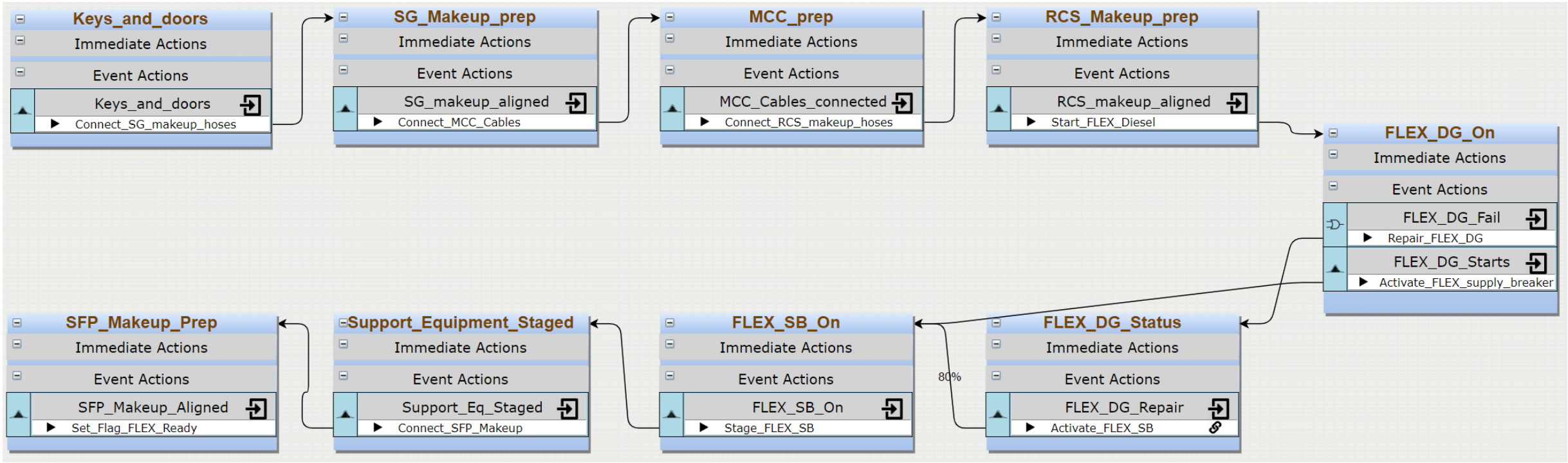






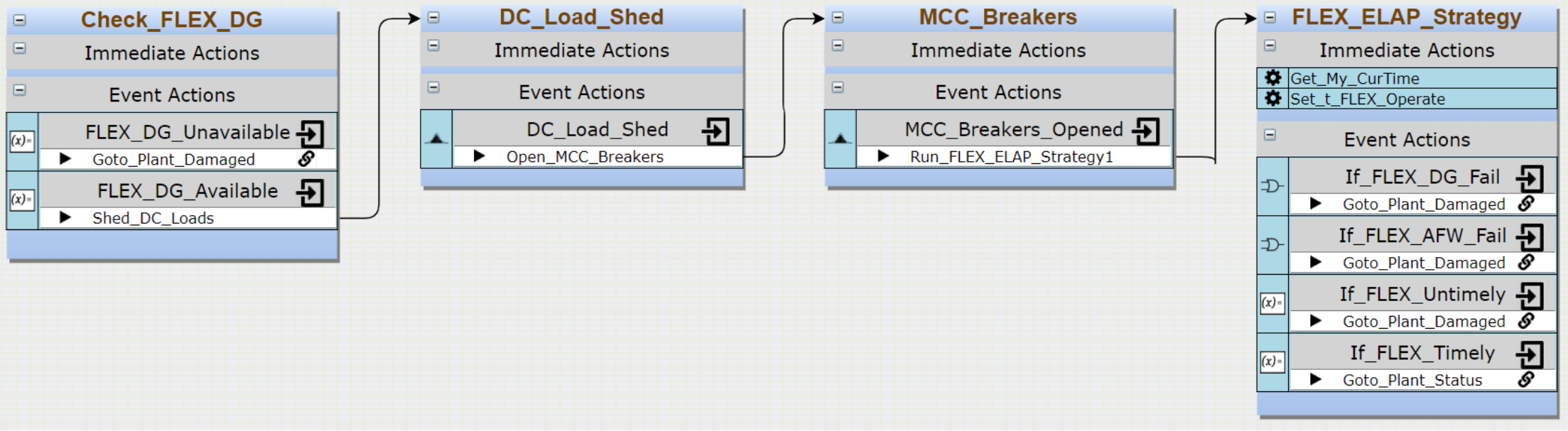


Serial FLEX Implementation

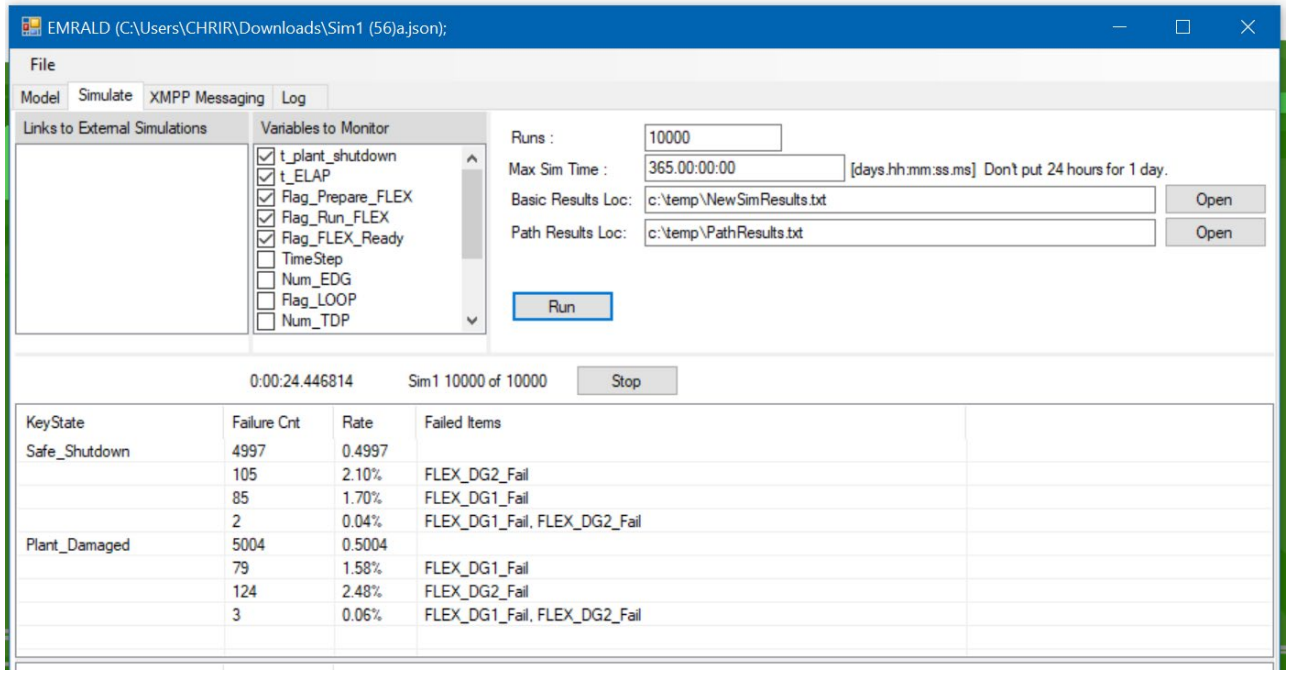


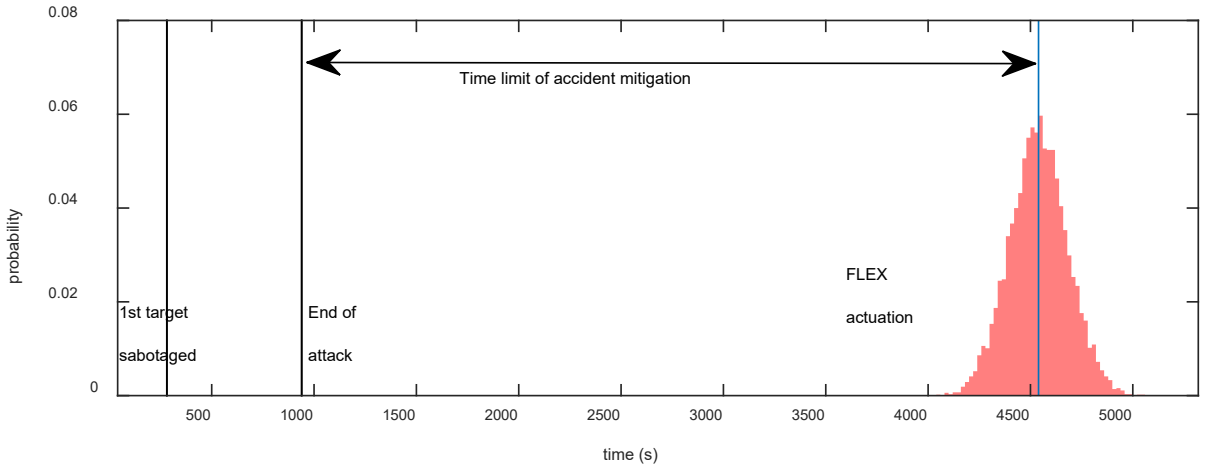
FLEX Strategies

If DB TDPs and EDGs are damaged: AFW circulation using FLEX SG makeup pumps and FLEX EDGs



Results



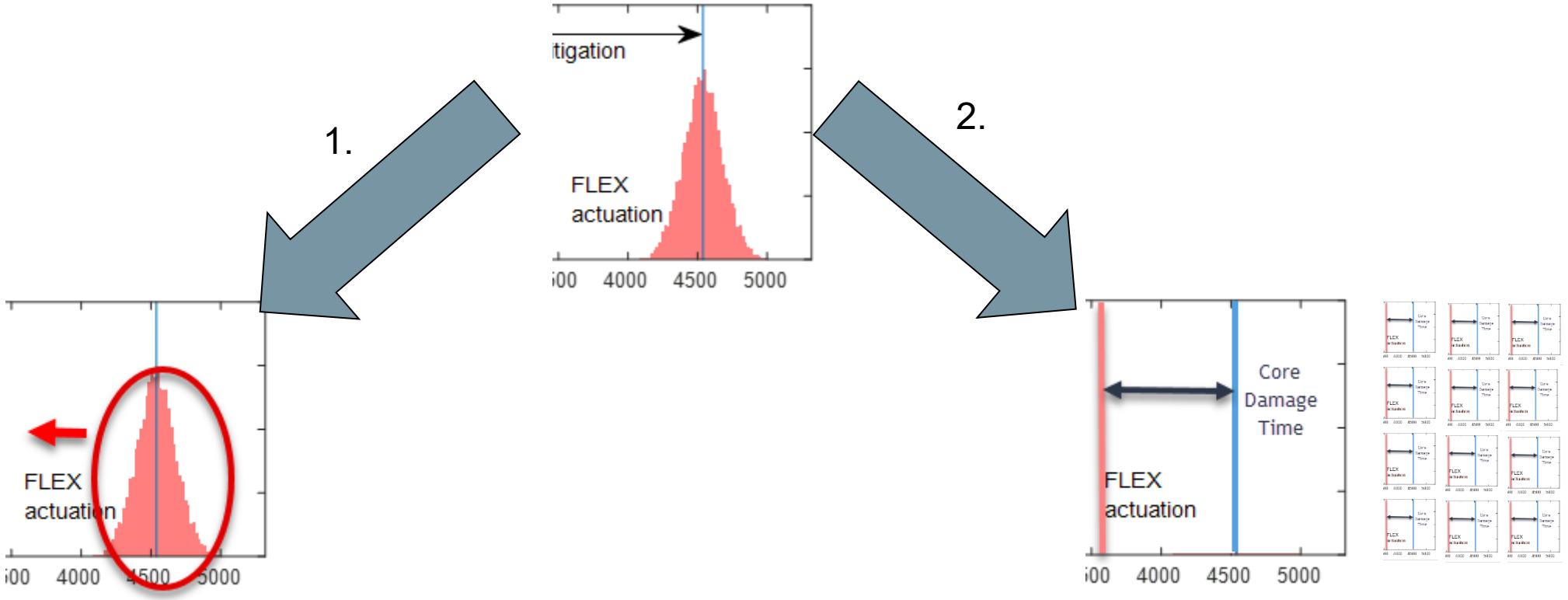


- Potential Flex Benefit
- Need rules for acceptance

FLEX Procedure or Model Optimizations

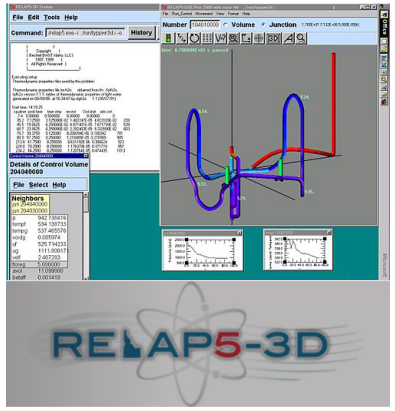
If initial FLEX modeling results are near static time limits two approaches can be taken.

1. Change FLEX procedures to reduce time requirements.
2. Perform dynamic analysis for each simulation cases to get custom time to core damage using thermal hydraulics analysis.

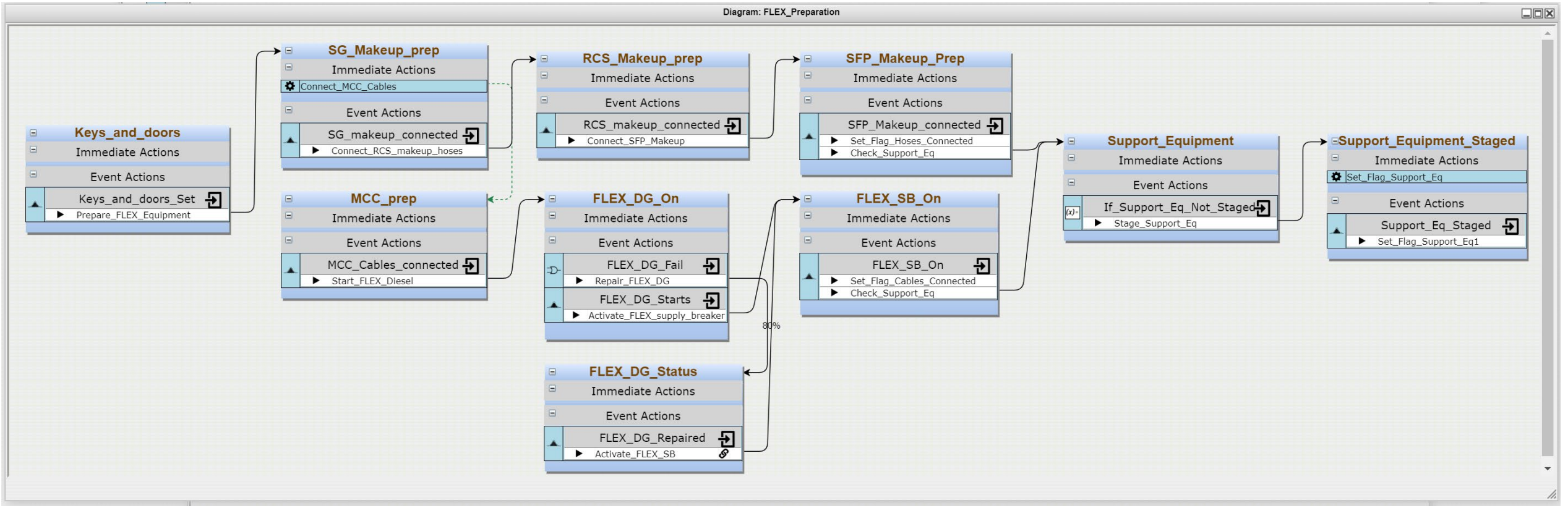


Current Work - Dynamic Analysis and Running Thermal Hydraulics

- Robby can you make a timeline for pulling events and putting into RELAP

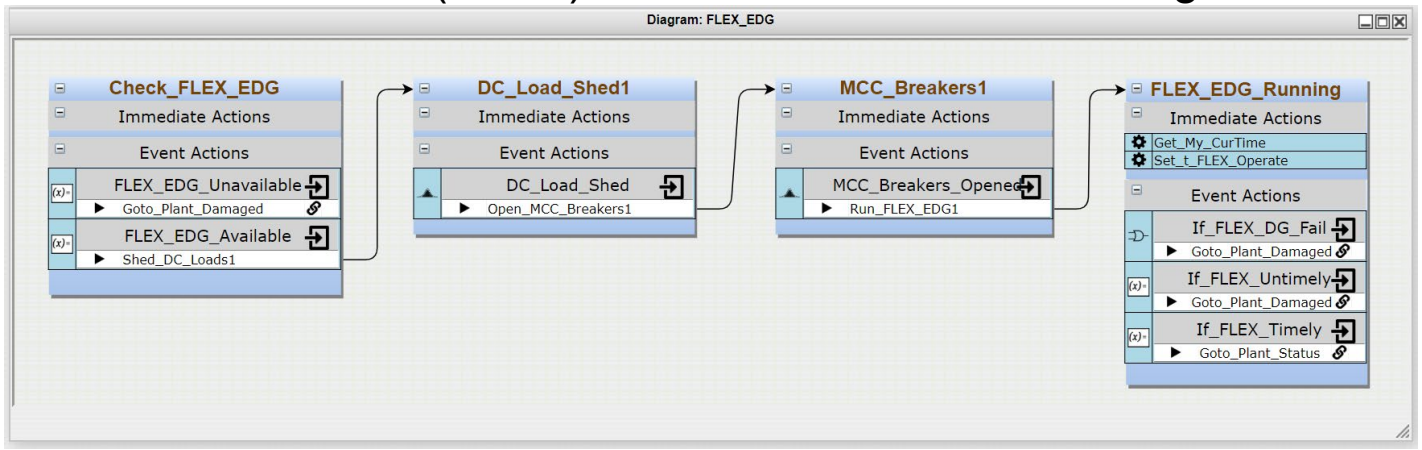


Change to Parallel FLEX Preparation

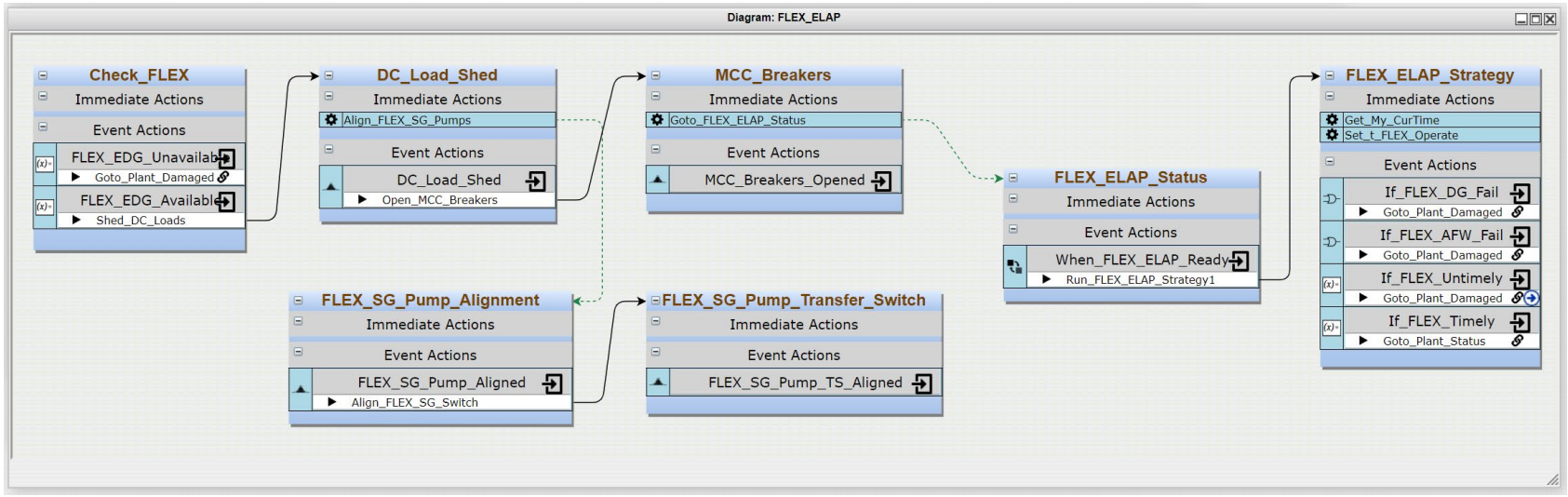


FLEX Strategies Serial vs Parallel

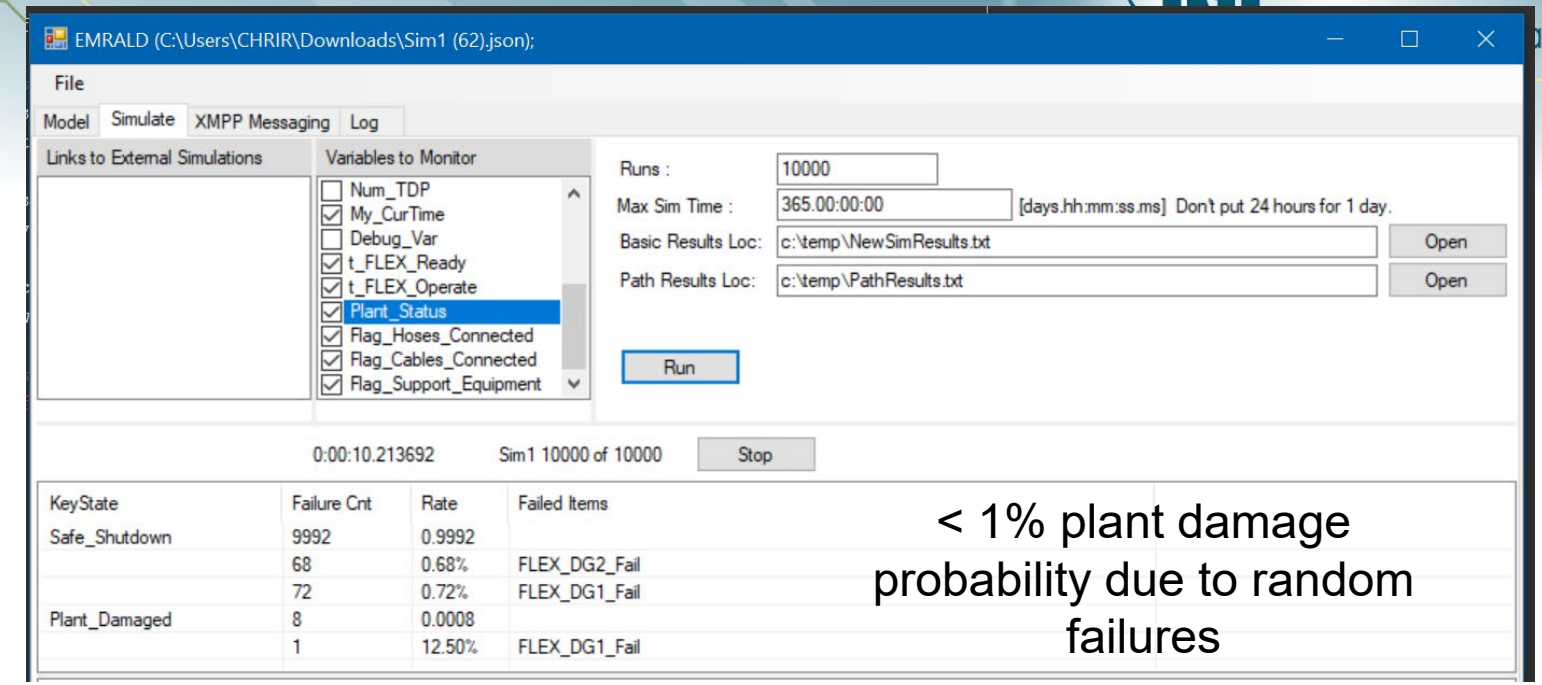
Total Loss of AC Power (TLAP): Use FLEX EDGs to recharge batteries of steam valves & instrumentations



TLAP & loss of feedwater: Use FLEX SG Pumps and FLEX EDGs

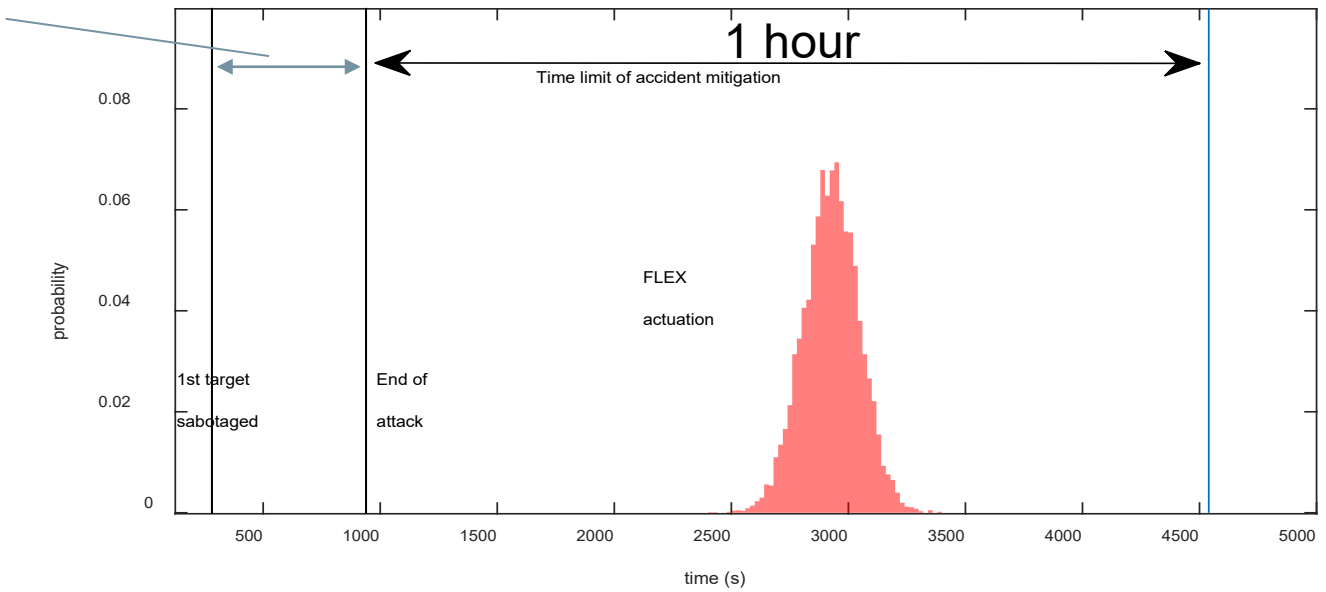


Results



< 1% plant damage probability due to random failures

Value of non-lethal denial (e.g. sticky foam, smoke generator)



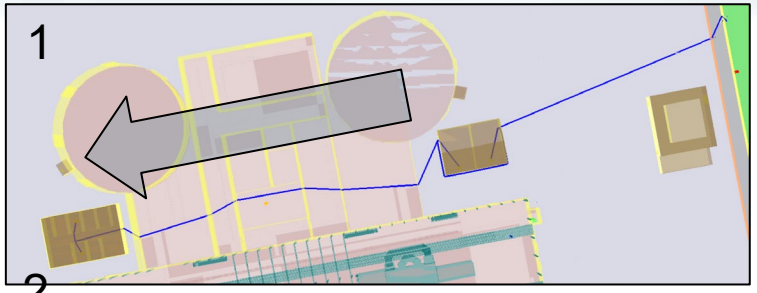
Results

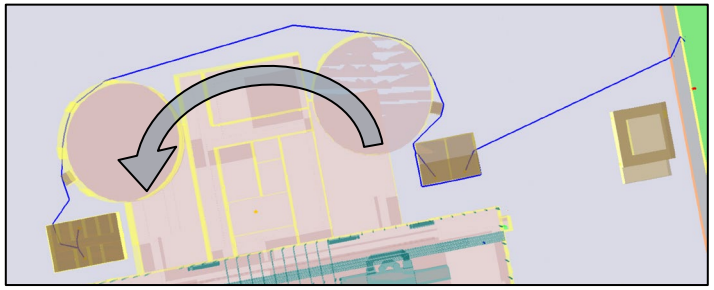
- Simulated 3 attack paths @ 100 runs

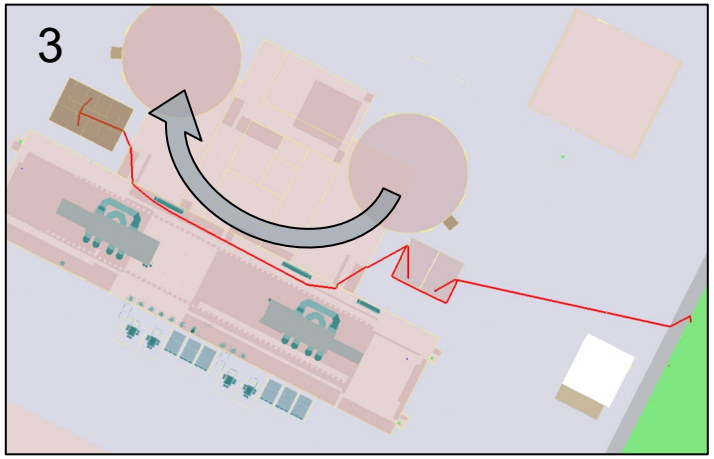
No.	System availability			Mitigation strategy	Probability	P(CD) without FLEX	P(CD) with FLEX
	Offsite power	EDG	TDP				
1	✓	✓	✓	N/A (Continue operation)	0	0	
2	✓	✓	×	Non-transient shutdown	0	0*1E-4	
3	✓	×	✓	Non-transient shutdown	0	0*1E-4	
4	✓	×	×	Non-transient shutdown	0	0*1E-3	
5	×	✓	✓	LOOP ET	280/300 = 0.933	0.933*1E-3	
6	×	✓	×	LOOP ET	0	0*5E-3	
7	×	×	✓	**FLEX** EDG strategy within 11 hours	17/300 = 5.67E-2	5.67E-2*4E-2	5.67E-2*1.54E-4
8	×	×	×	**FLEX** ELAP strategy within 1 hour	3/300 = 0.01	0.01*1	0.01*1.83E-4
Total					1	1.32E-2	9.44E-4

FLEX use reduces Core Damage Probability

- With FLEX (1 team): 5.94E-3
- With FLEX (2 teams): 9.44E-4







Current Work – BRE Configuration

BRE Configuration Optimization

- Support improvement in current configuration
- Support new capital investments in BRE
- Use dynamic modeling to identify the most effective number of BREs and their location
- Can be applied to other equipment such as remote operated weapons

Idaho National Laboratory