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Probabilistic Methods for Cyclical and Coupled Systems with Changing Failure Rates

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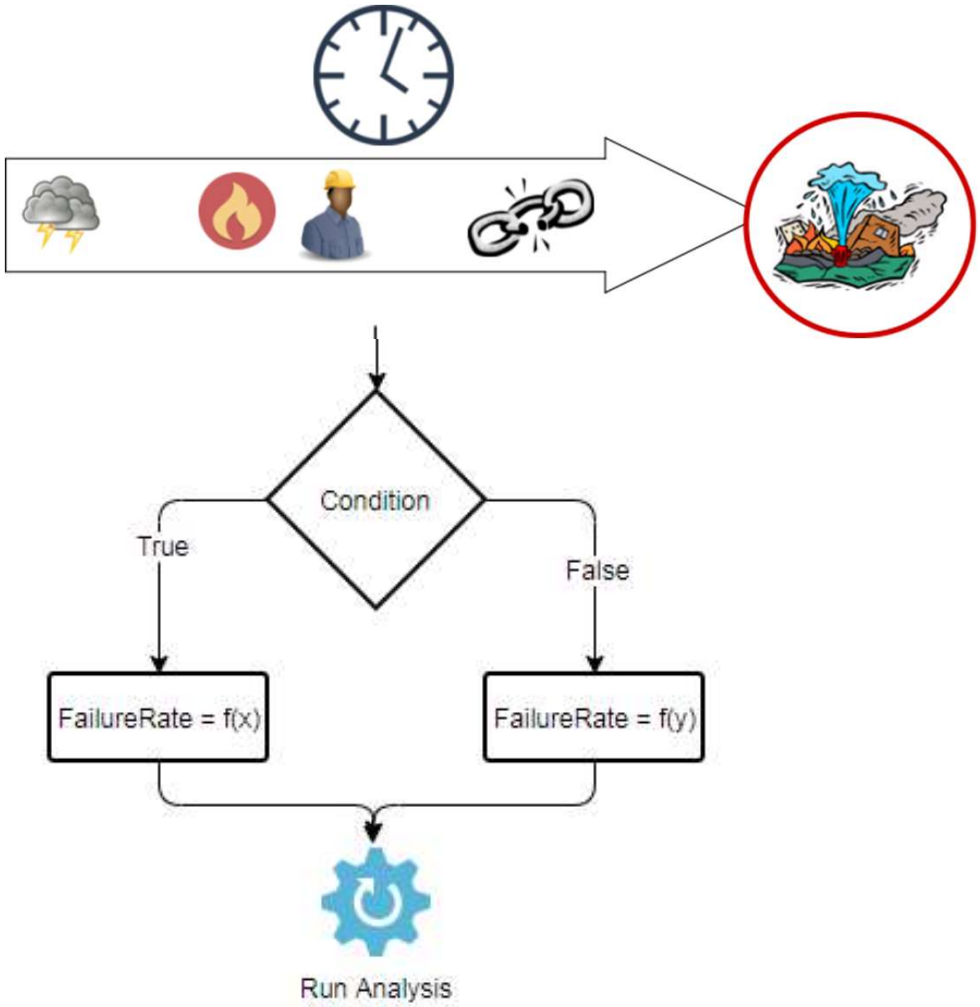
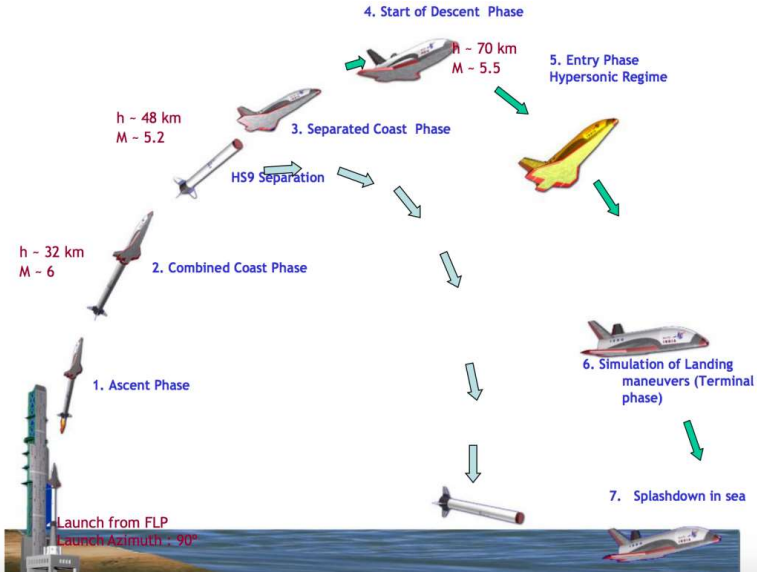
Dynamic PRA

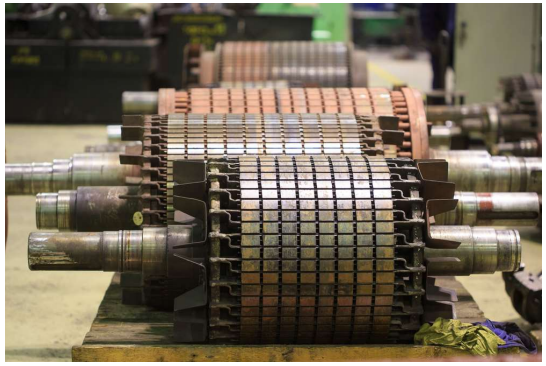
- Accounts for order and time of failures
- Can model looping or feedback
- Handles conditional rates
- Couples with other analysis tools
- Promises increased realism



Changing Distribution Parameters

- **Aerospace modeling** – different mission phases and changing component or system failure rates for different phases of the mission, such as launch, orbit, and reentry
- **Degraded components** – induce other failure modes, causing a change in the failure rate
- **Environmental conditions** – events, such as algae blooms, can cause heat sink reduction, reduce output capabilities, or affect support systems
- **Degradation and preventative maintenance** – predictive monitoring of nuclear plant components

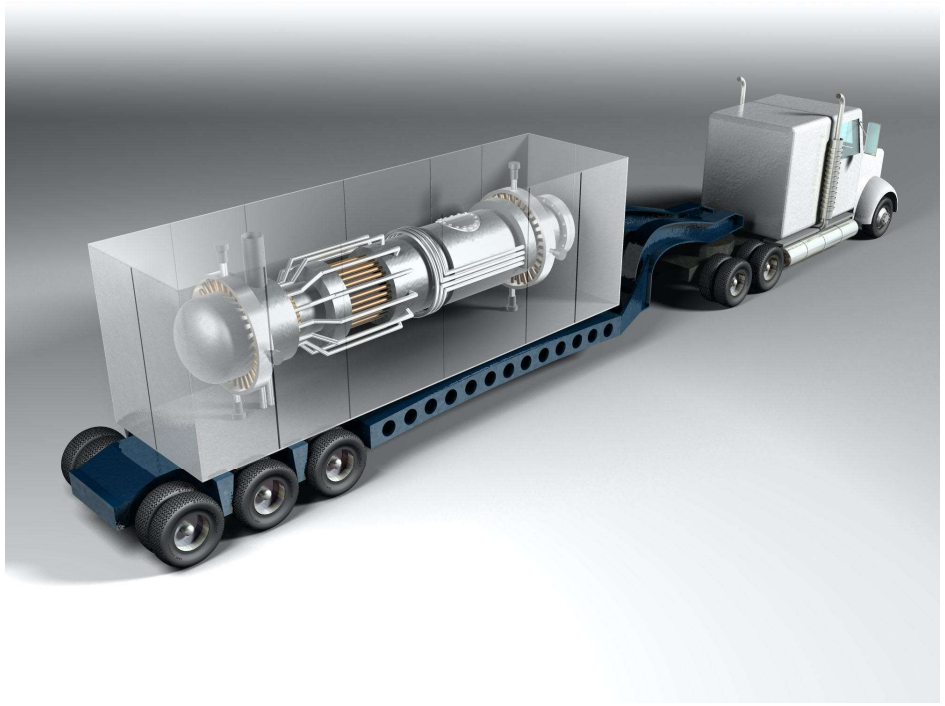




Fission Battery Risk and Reliability Modeling

Fission Battery

- Autonomous
- Standardized
- Installed
- Reliable
- Economic



Dynamic Modeling Needs

- Feedback Loops
- Physical & Cyber Security
- Reliability & Lifespan

EMRALD

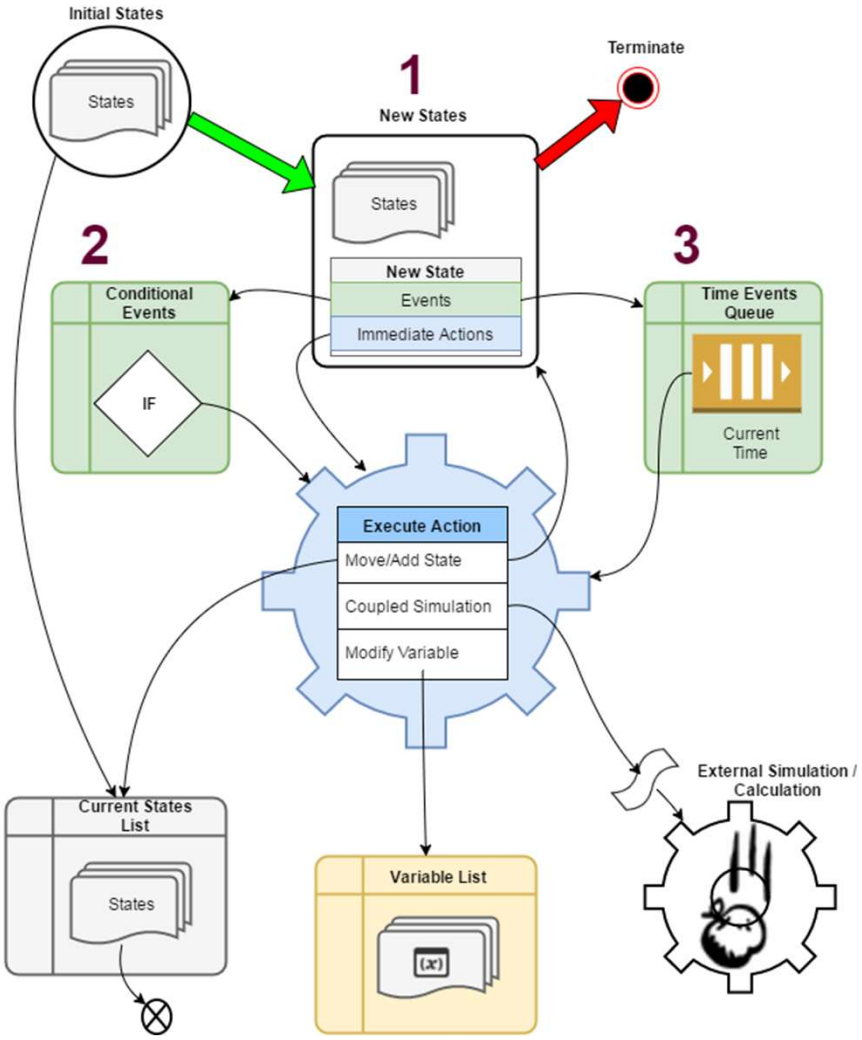
Dynamic PRA based on a three-phased discrete event simulation

Initialization – Start states added to initial states

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)

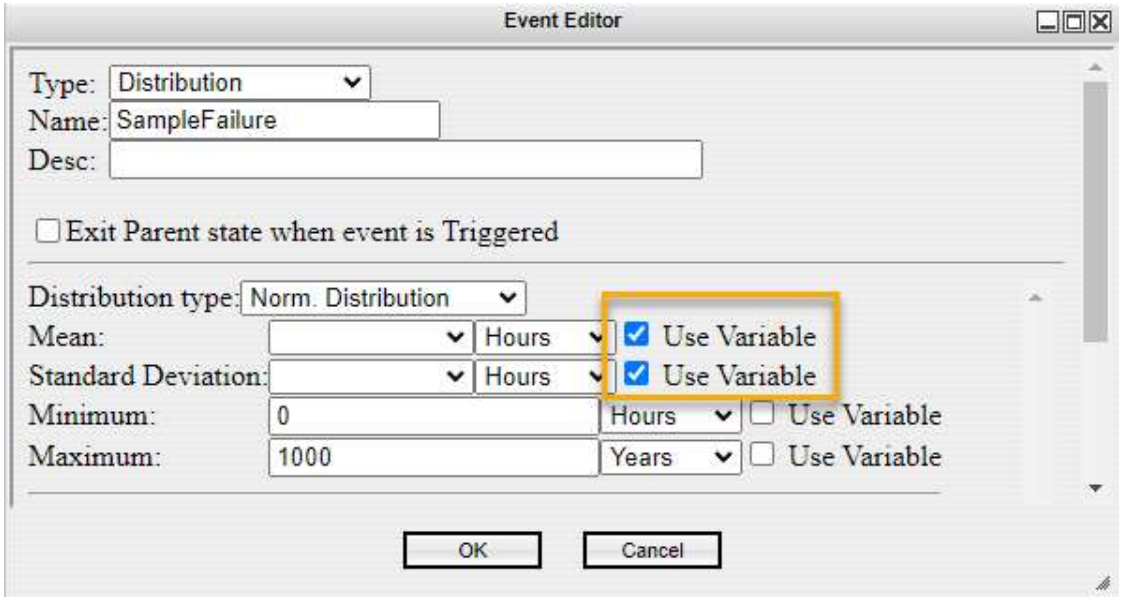
3. Jump to the next chronological event
   - Process that event's actions
   - (Go to Step 1)

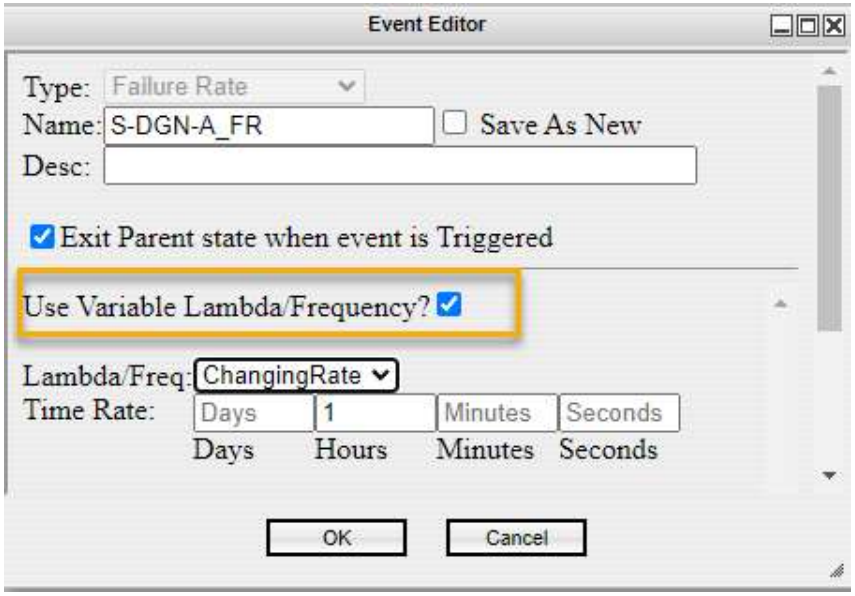


https://emrald.inl.gov

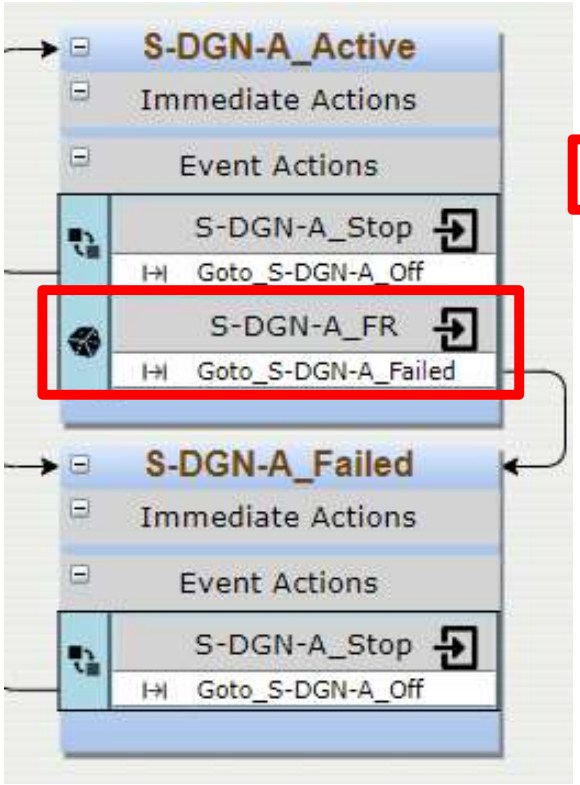
Variables in Distributions

Feature to select the use of variables in sampling





Sampling Problem



EMRALD Steps on entering a state:

1. Run any immediate actions
2. Sample any time distribution events
3. Evaluate condition-based events and execute actions if met

Problem:

If a distribution for an event has been sampled, and then something adjusts the parameters for that sampling, what should be done?

Sampling Problem Example

Micro reactor designed to load follow

- Normal operation failure rate of 0.01 per 24 hours
- Can run up to 110% of design but increase the failure rate
- Demand of 101–110% once per day
- Resamples failure time on change (same failure rate)

Method using 1,000 Runs	MTTF (Days.Hours)
Fixed Lambda (0.01 per 24 hours)	90.23
Resample Lambda (0.01 per 24 hours)	11.14

Modeling Options on Change

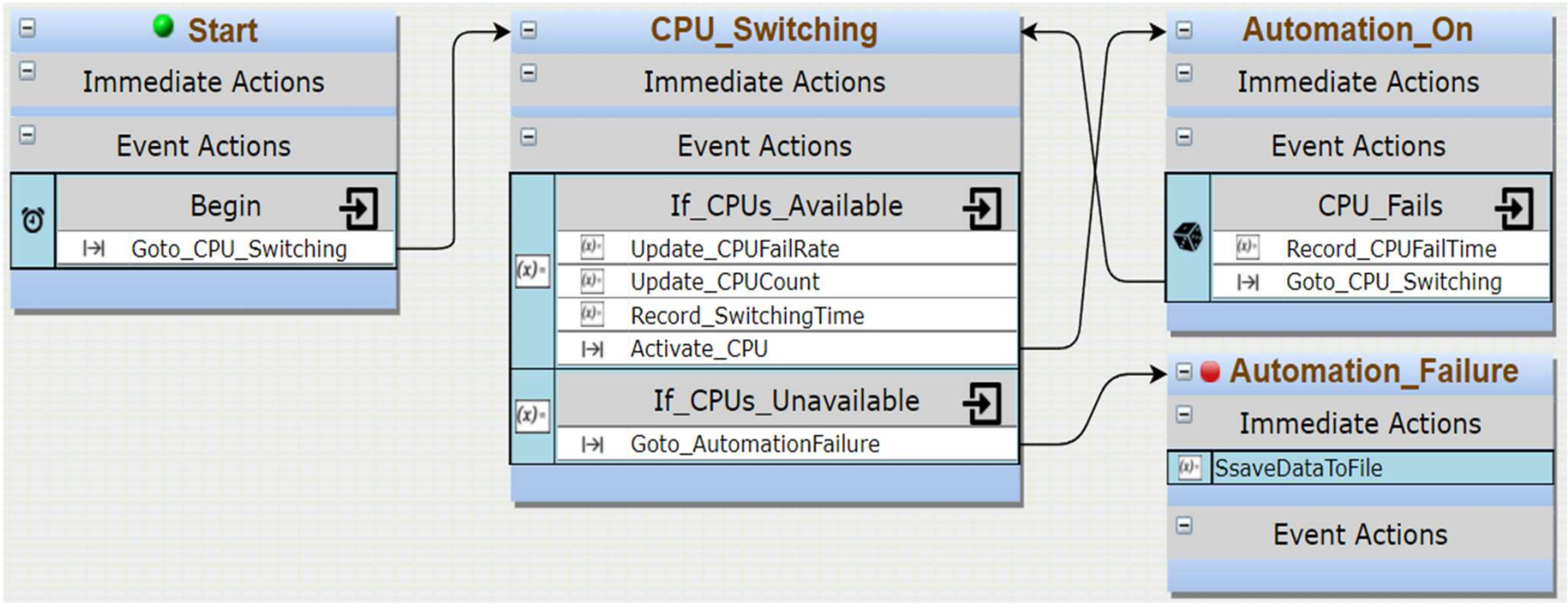
Ignore

Resample

Adjust

Resample Example

Fission battery with redundant CPUs: if first fails, the second replaces it.



Resample Method

- Old occur time and new occur time of sampled events are independent
- Resample distribution with changed input parameters
- Replace failure time

Poisson Process following an Erlang Distribution

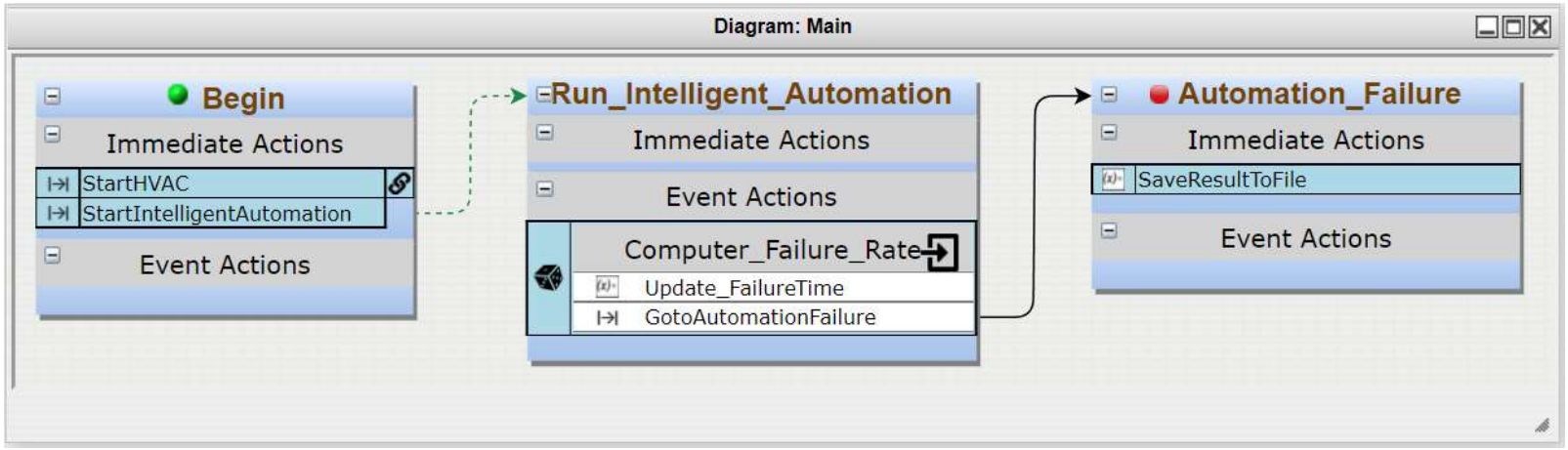
- $1 - e^{-\lambda t}$

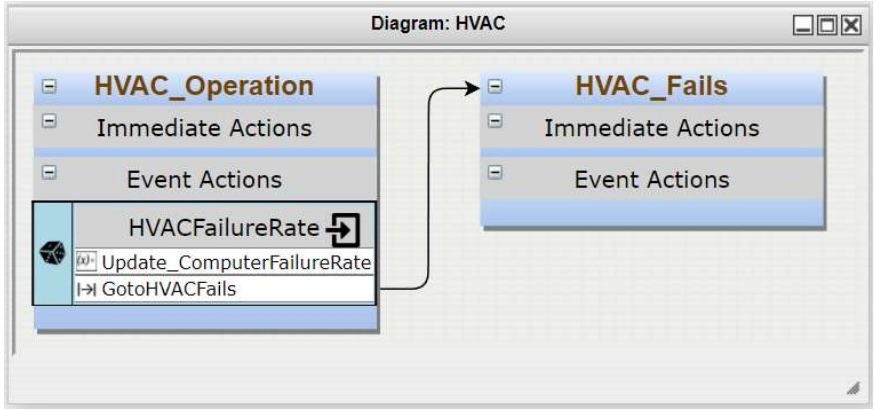
Probability Integral Transformation

- $\Delta t = \frac{ln[1-ra \quad (0,1)]}{-\lambda}$

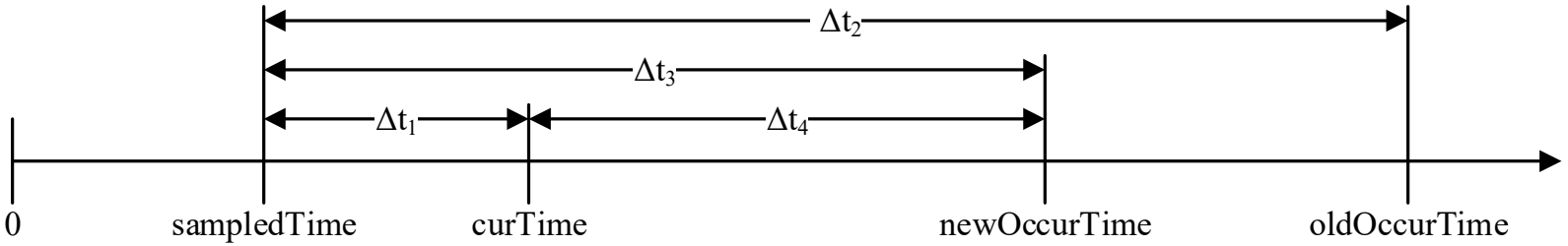
Adjust Example

Fission Battery Computer system adjusted with primary HVAC failure. (1E-3/hr to 5E-3/hr)





Adjust Method – New Failure Formula Given Time Has Passed



$$\lambda_C = \begin{cases} \lambda_1, t < curTime \\ \lambda_2, t \geq curTime \end{cases}$$

Conditional probability

- $R(\Delta t_4|\Delta t_1) = \frac{R(\Delta t_3)}{R(\Delta t_1)} \leftrightarrow R(\Delta t_3) = R(\Delta t_4|\Delta t_1) * R(\Delta t_1)$

Reliability and failure

- $R(\Delta t) = 1 - F(\Delta t) \leftrightarrow F(\Delta t) = 1 - R(\Delta t)$

Combined in terms of failure probability

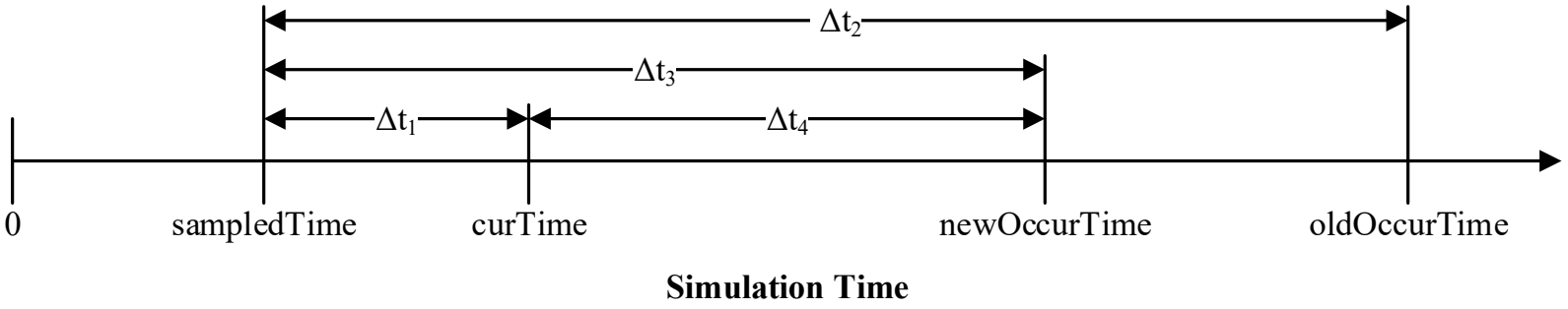
- $F(\Delta t_3) = 1 - [1 - F(\Delta t_1)] * [1 - F(\Delta t_4|\Delta t_1)]$

R(Δt) Reliability

F(Δt) Failure

Δt time to transition to an event

Adjust Method (Continued)



$$\lambda_C = \begin{cases} \lambda_1, t < curTime \\ \lambda_2, t \geq curTime \end{cases}$$

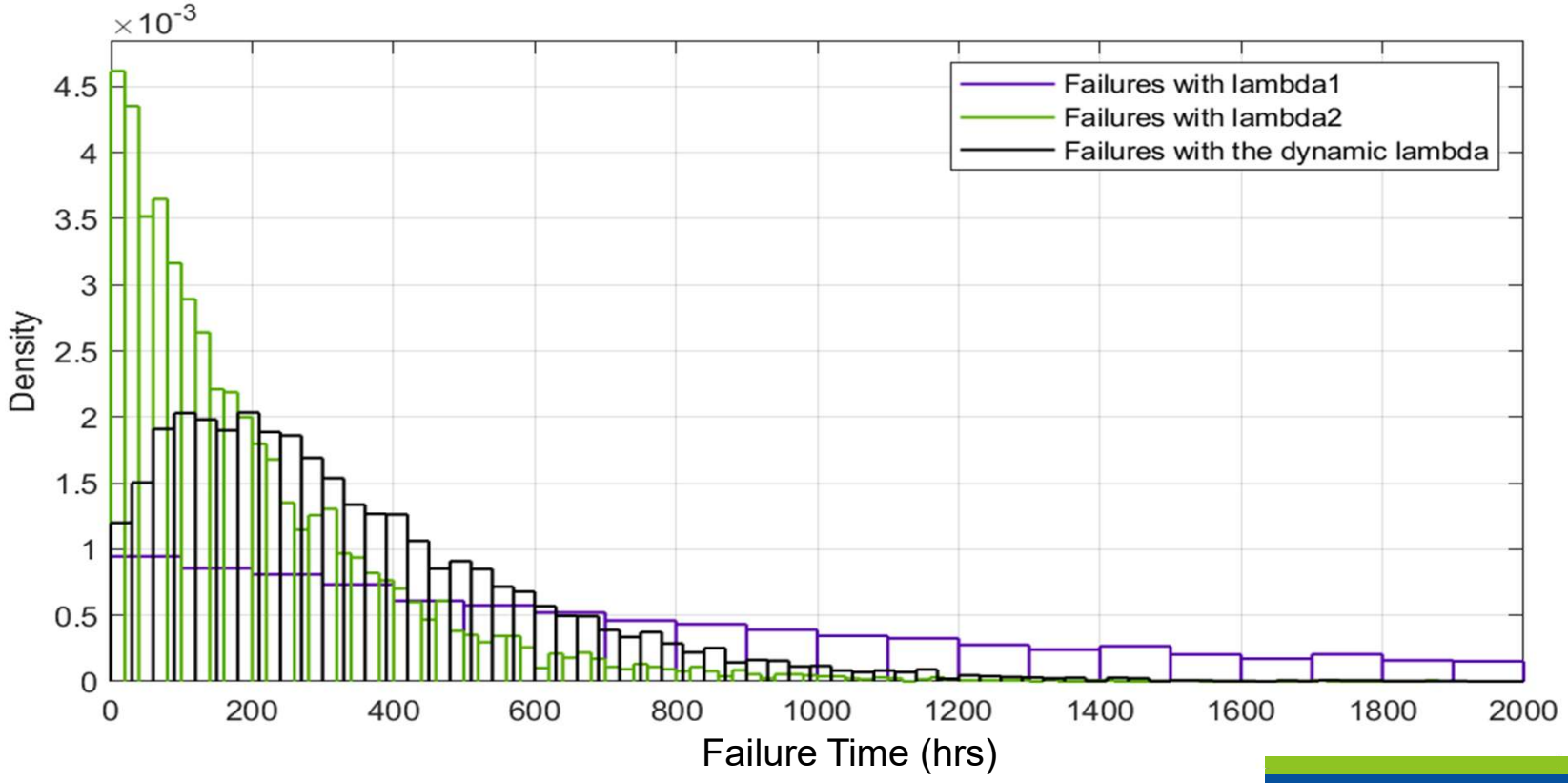
Using - $F(\Delta t_3) = 1 - [1 - F(\Delta t_1)] * [1 - F(\Delta t_4 | \Delta t_1)]$

Using Erlang distribution $1 - e^{-\lambda t}$

1. Assumed – oldOccurTime is given from previous probability integral transformation.
2. Substitute times on right hand side (See Paper)
   - $F(\Delta t_1) = 1 - e^{-\lambda_1 \Delta t_1}$
   - $F(\Delta t_4 | \Delta t_1) = 1 - e^{-\lambda_2 \Delta t_4}$
3. Use probability integral transformation on result for newOccurTime

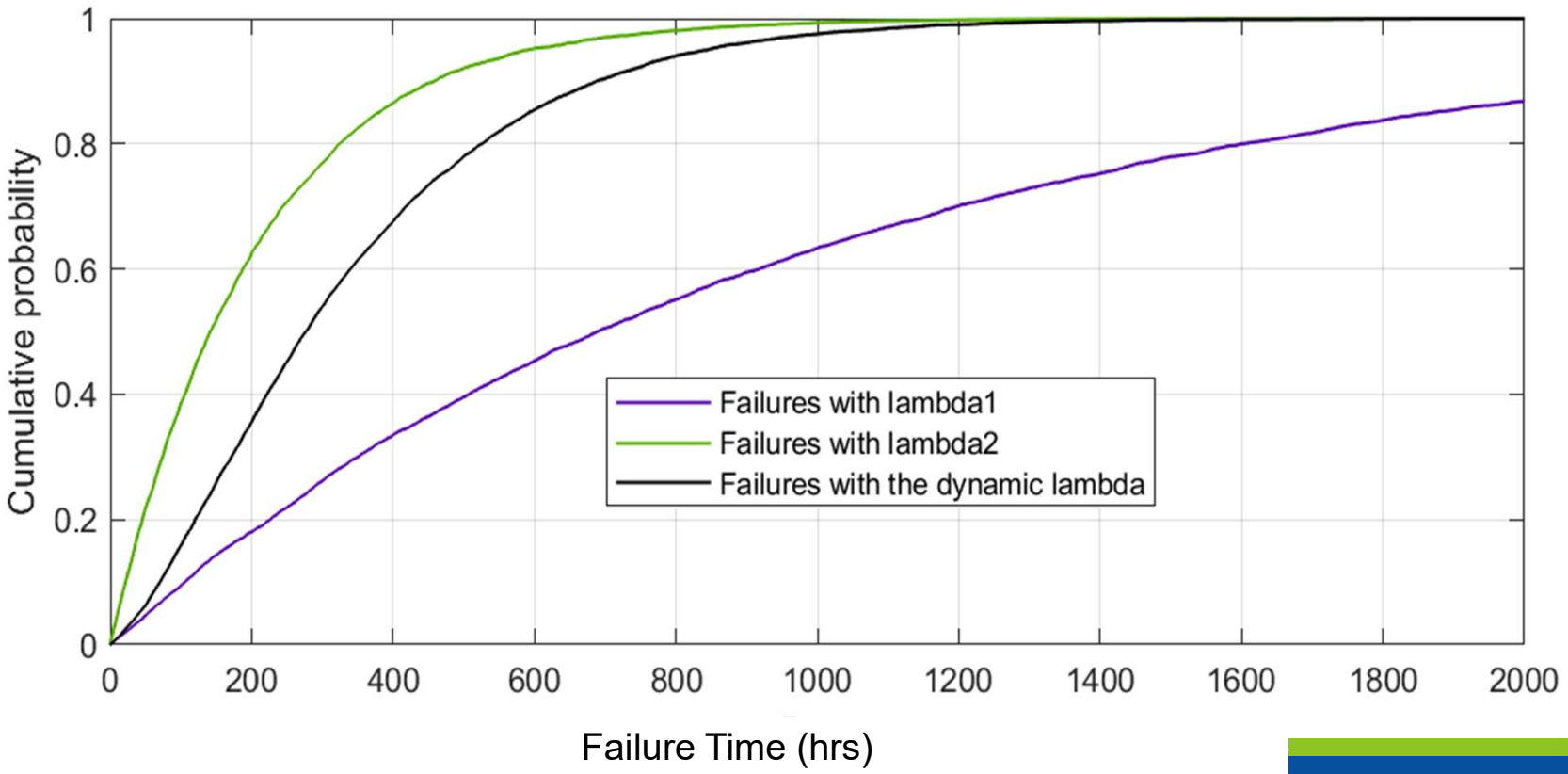
Results

Probability density of single component failure time (10,000 runs)



Results

Cumulative probability of single component failure time (10,000 runs)



Conclusion

- Dynamic PRA enables new model options
- Multiple options are needed for what to do on changing distribution parameters
- Modelers need to understand when to use change options

A base equation for “adjusting” a sampled distribution was developed and tested with the Erlang distribution for a Poisson process.

The same function can be applied to multiple distributions.

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Option Added to EMRALD