An Integration Platform for Dynamic Reliability Analysis in Living PSA Context

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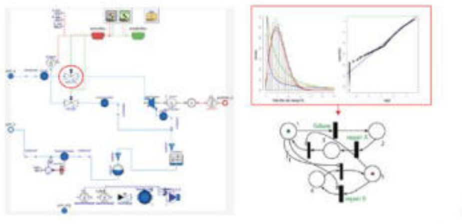
Motivation & Purpose

- Recent advances in the development of digital intelligence offer new opportunities to reshape the nuclear industry.
  - Digital Instrumentation and Control System Technologies (Smart Sensors, Digital Distributed Networks, Software Controls, Internet of Things, etc.)
  - Big Data, Data Science/Analytics, Data/Text Mining
  - Machine Learning, Artificial Intelligence
  - ....
- How digital and intelligent solutions can help promote the safety, operational efficiency and resilience of NPPs has come into focus in recent years.
  - Online monitoring, visualization, digital twins real-time simulation, diagnosis and prognosis, risk management, …

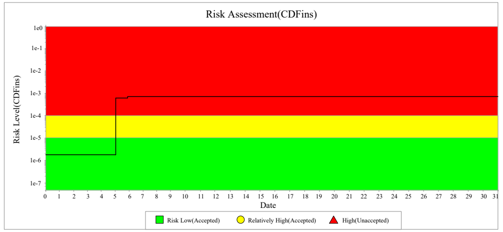


Motivation & Purpose

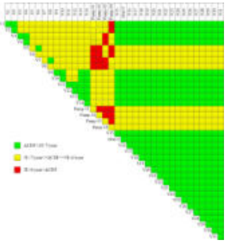
- The purpose of this study is focus on the development of **An Integration Platform for Dynamic Reliability Analysis in Living Probabilistic Risk Assessment (Living PSA) Context** with a hybrid compute engine implemented by Dynamic Event Tree (DDET), Markov/Cell-to-Cell-Mapping Technique (Markov/CCMT), and GO-FLOW Methodology (GO-FLOW).
  - Linking of Boolean models with analytical solutions
  - Taking into account dynamic characteristics of event sequence progressing and process interactions under uncertainties.
  - Extending dynamic reliability assessment of digital I&C systems for Living PSA.
  - Moving beyond risk-based performance monitoring and safety management from multidimensional perspectives (i.e., success/failure, goal-oriented, functional, etc.), …



Reliability Modeling and Analysis



Risk Monitoring



Risk Matrix

Risk Management

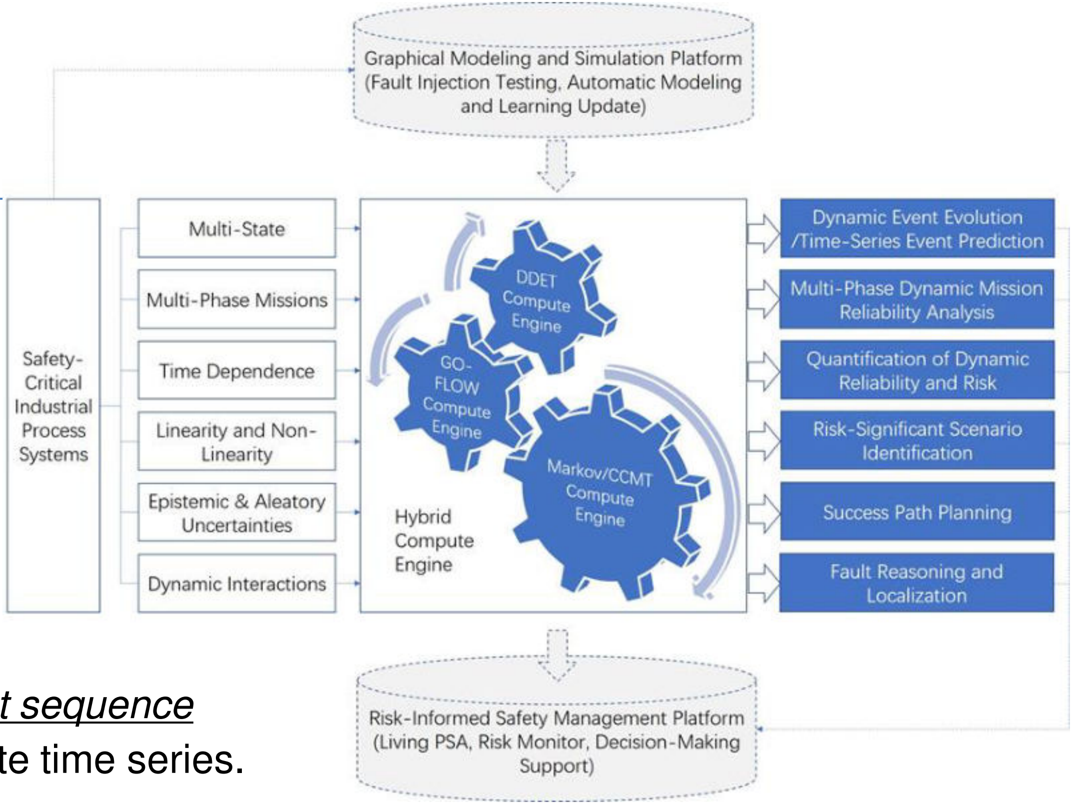
Hybrid Compute Engine — **Markov/CCMT** — **DDET** — **GO-FLOW**

Primarily aims for:

— Safety assessment and verification of DI&C systems

— Living PSA

— Risk monitor and intelligent decision-making support

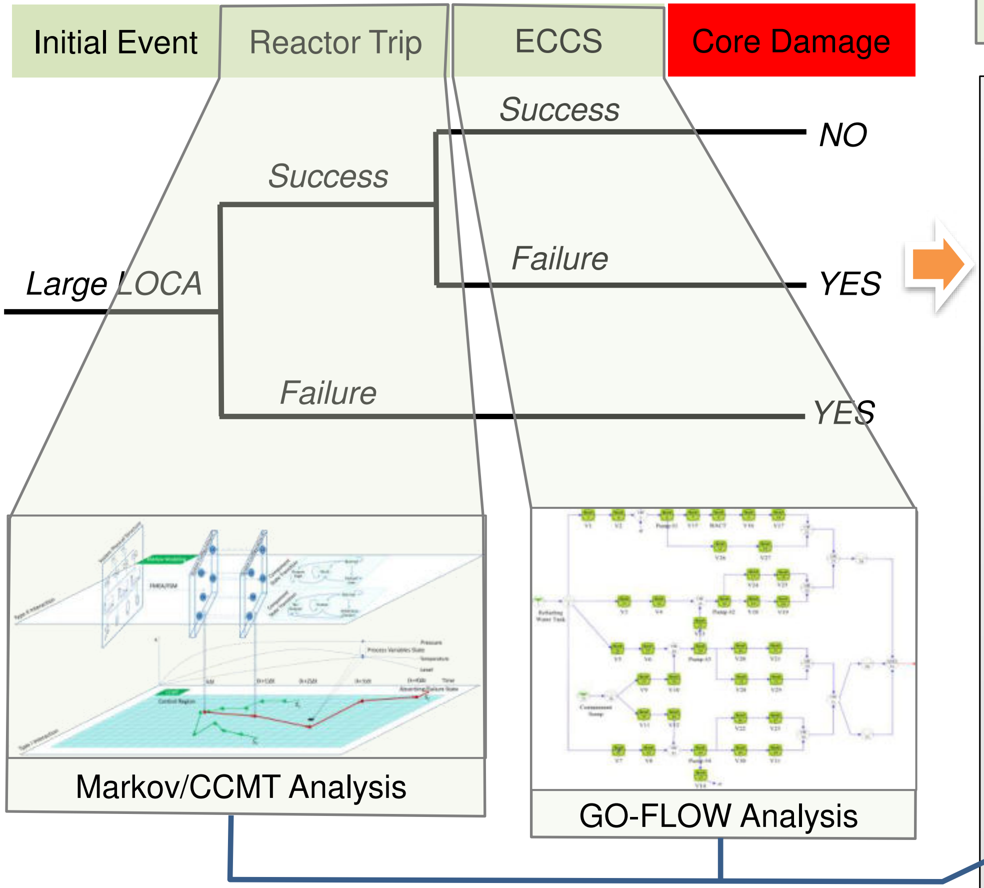


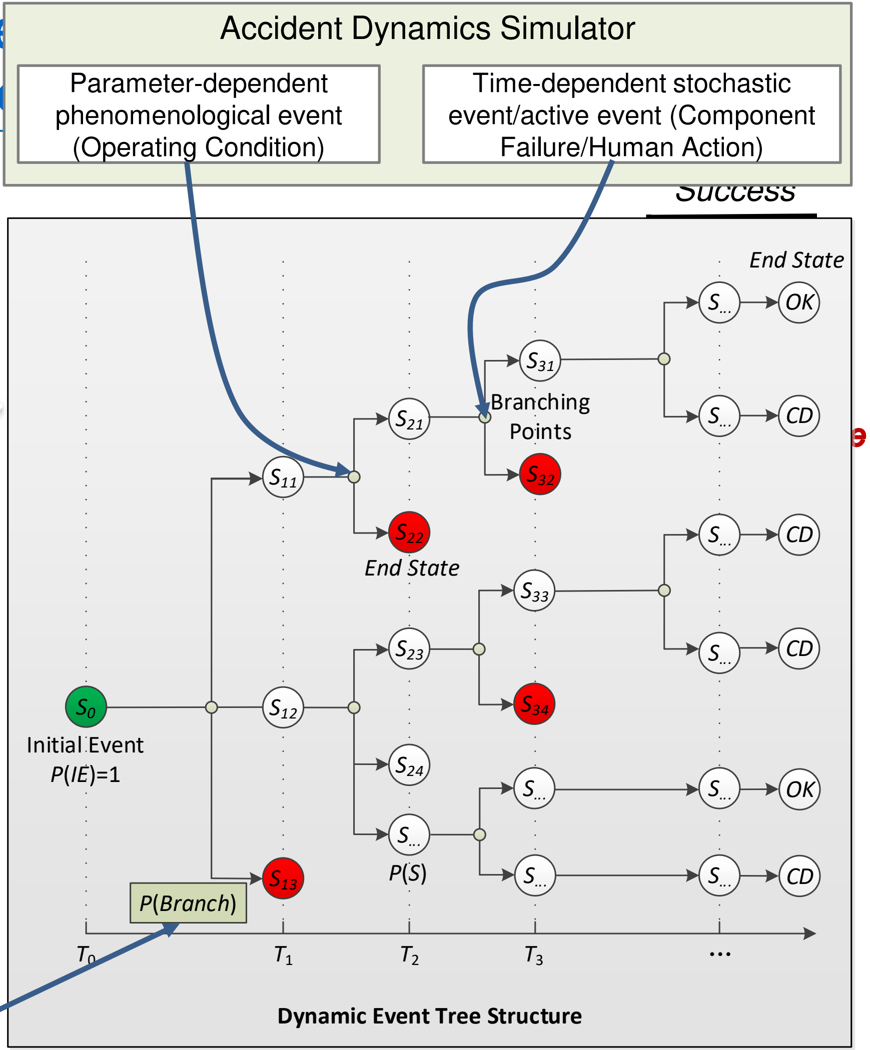
DDET: Simulate the *dynamic accident sequence* coupled with system failures in discrete time series.

Markov/CCMT: Interpret *process interactions* involved with components failures, variable events and human behaviors in *dynamic systems* by a probabilistic mapping scheme.

GO-FLOW: Apply for *time-dependent reliability* modeling and analysis of *Engineered Safety Features with multi-phase missions* and even with loop structures.

Hybrid Compute Engine Implemente
Reliability Analysis in Living PSA Co





Markov/CCMT: Simulation-based Fault Injection Machine

- Generation of probabilistic mapping scheme (Markov/CCMT model)

(1) Continuous Integration

$$\mathbf{Q} = Q(m, j \mid m', j', \Delta t) = G(j \mid j', m', \Delta t) \cdot H(m \mid m', j' \rightarrow j, \Delta t)$$

$$H(m \mid m', j' \rightarrow j, \Delta t) = h(c \mid c') = h_1(c_1 \mid c_1')h_2(c_2 \mid c_2')h_3(c_3 \mid c_3')$$

$$G(j \mid j', m', \Delta t) = \frac{1}{\upsilon_{j'}} \int_{V_{j'}} dx' \, e_j[x(x', m', \Delta t)]$$

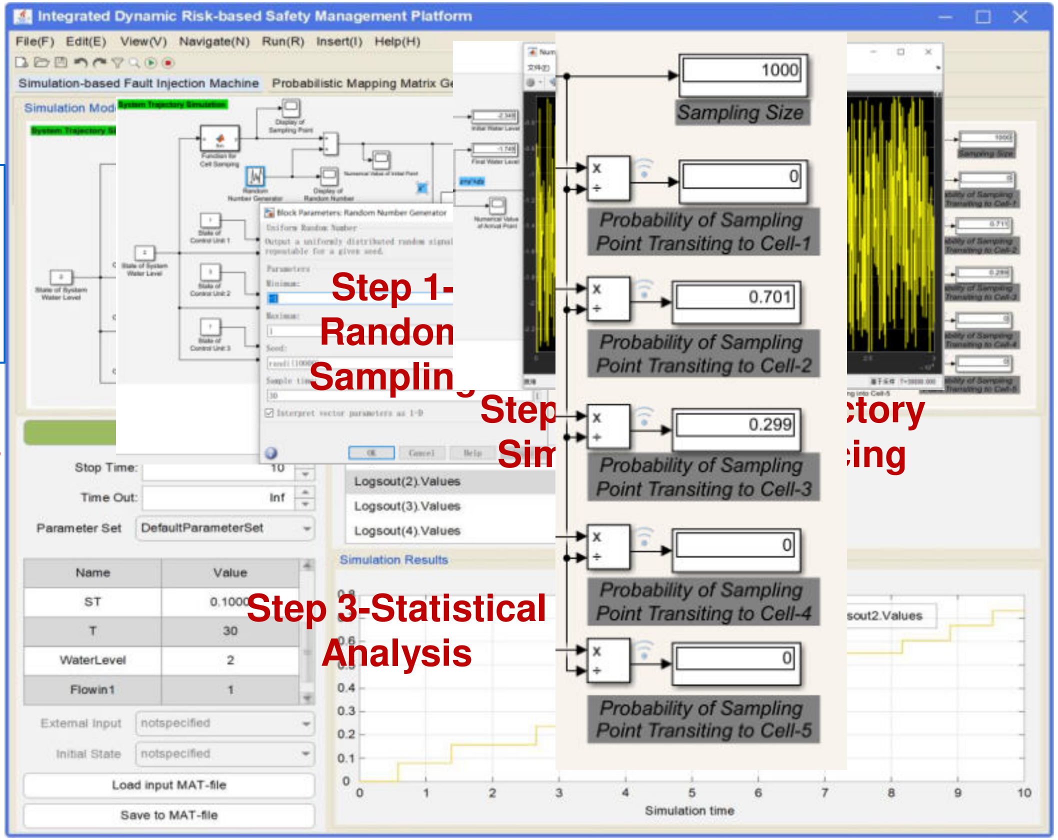
$$e_j[x(x', m', \Delta t)] = \begin{cases} 1 \; if \; x \in V_j \\ 0 \; otherwise \end{cases}$$

Analytical solution may not always be possible owing to the non-linear aspects

(2) Equal-weight quadrature scheme

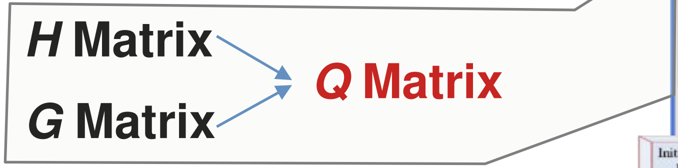
Implemented by the simulation-based fault injection testing with Monte Carlo sampling and path tracing.

- Random Sampling
- System Trajectory Simulation and Tracing
- Statistical Analysis

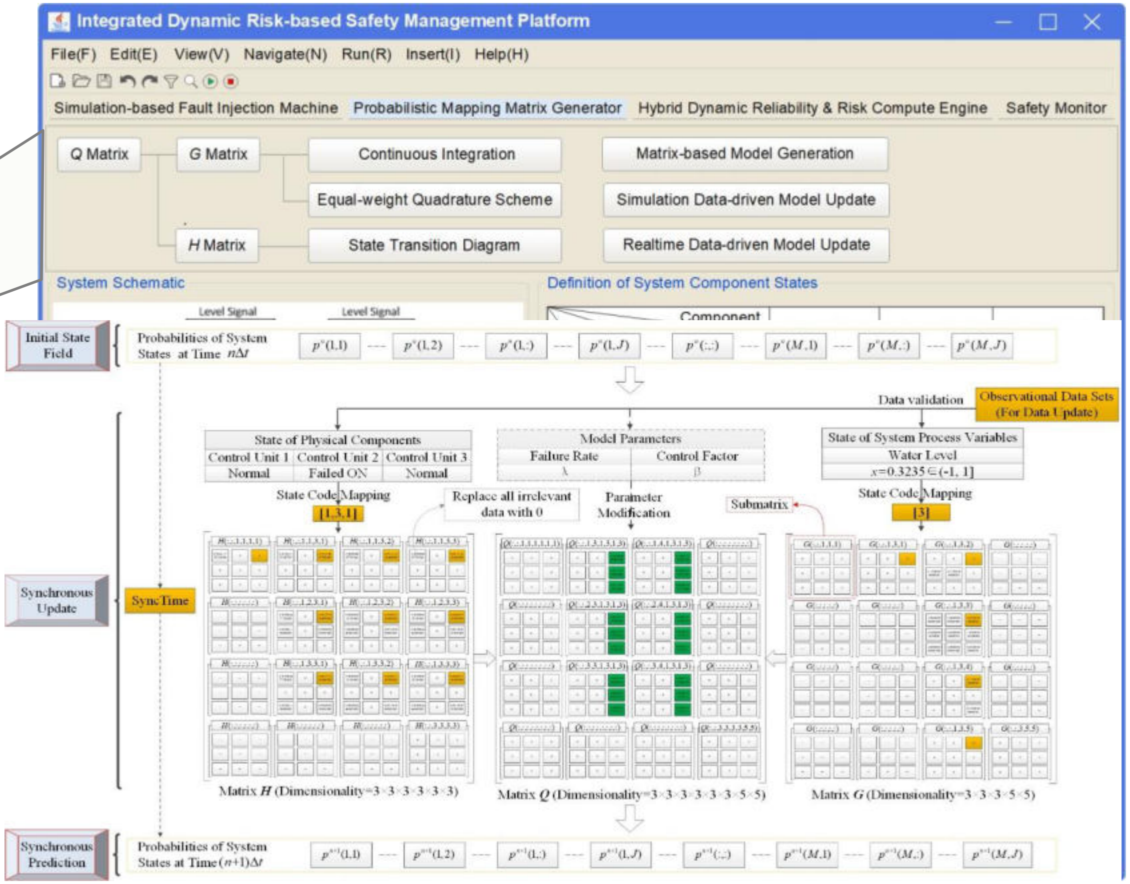


Markov/CCMT: Probabilistic Mapping Matrix Generator

- Matrix-based infrastructure implemented for probabilistic mapping scheme generation



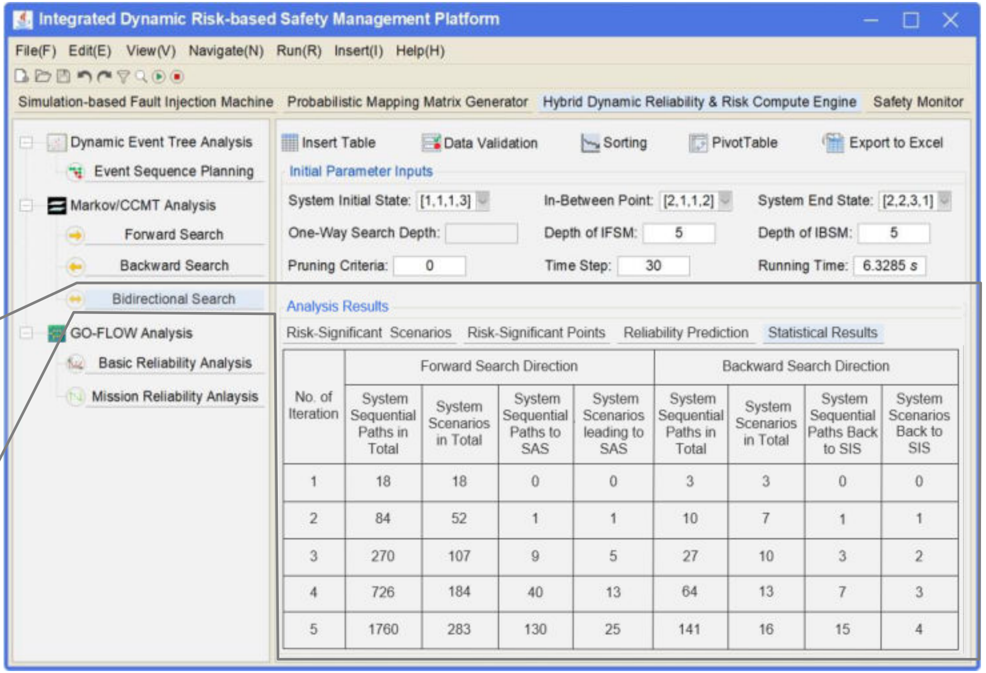
- Unsupervised machine learning for Markov/CCMT model update
  - Simulation Data-driven Model Update
  - Realtime Data-driven Update



Markov/CCMT: Risk-based Dynamic Reliability Analysis

- The hybrid compute engine consists of:

1. A Dynamic Event Tree Planning Algorithm
   – Event Sequence Planning
2. A Versatile Markov/CCMT Search Algorithm
   – Forward Inductive Analysis
   – Backward Deductive Analysis
   – **High-Efficiency Bidirectional Analysis**
3. An Optimized GO-FLOW Algorithm
   – Basic Reliability Analysis
   – Mission Reliability Analysis



No. of Iteration	Forward Search Direction				Backward Search Direction			
	System Sequential Paths in Total	System Scenarios in Total	System Sequential Paths to SAS	System Scenarios leading to SAS	System Sequential Paths in Total	System Scenarios in Total	System Sequential Paths Back to SIS	System Scenarios Back to SIS
1	18	18	0	0	3	3	0	0
2	84	52	1	1	10	7	1	1
3	270	107	9	5	27	10	3	2
4	726	184	40	13	64	13	7	3
5	1760	283	130	25	141	16	15	4

The bidirectional search results obtained in our previous study [1] shows that the efficiency has been greatly improved using bidirectional solver (**6.3285 seconds**) than single direction search (**1828.8 seconds** for the backward search and **35517.1 seconds** for the forward search).

[1] Jun Yang, Chenyu Jiang, Zhihui Xu, Mengkun Li, Ming Yang. Markov/CCMT: towards an integrated platform for dynamic reliability and risk analysis. Process Safety and Environmental Protection, 155: 1-20, 2021.

Success Path Planning

- A flexible optimization algorithm for GO-FLOW methodology[2] to deal with shared signals is newly proposed to provide **exact solutions with high computational performance**.
- The backtracking **decoding of number clustering of complete minimal path sets** obtained by qualitative GO-FLOW analysis can be implemented for **success path regeneration**.

[2] L. C. Zheng, X. Y. Dai, J. Yang, et al. A flexible optimization algorithm for GO-FLOW methodology to deal with shared signals. Annals of Nuclear Energy. 156(108200): 1-15, 2020.

- The success paths for achievement of Goal-2 from functional perspectives include:

Success Path-1: MPS {1, 6, 7, 8, 9, 10, 21}

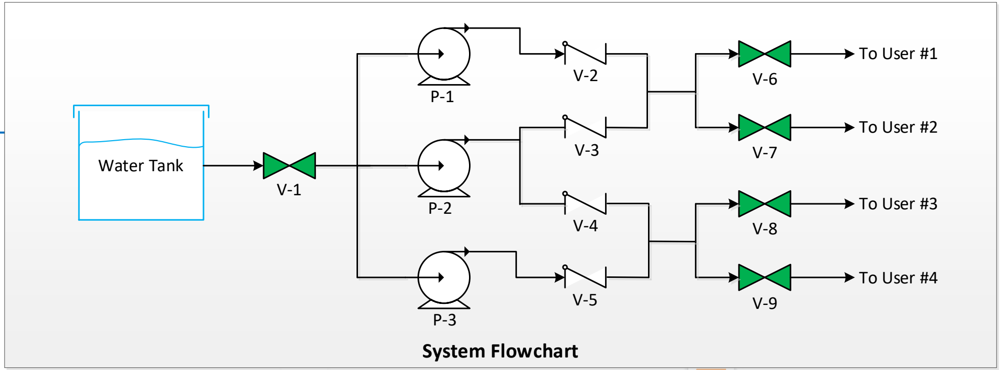
P(Success Path-1)=0.9983400

{Water tank with water, Open Valve V-1, Open Pump P-1, Keep P-1 operation for 2 hours, Open Valve V-2, Open Valve V-7}

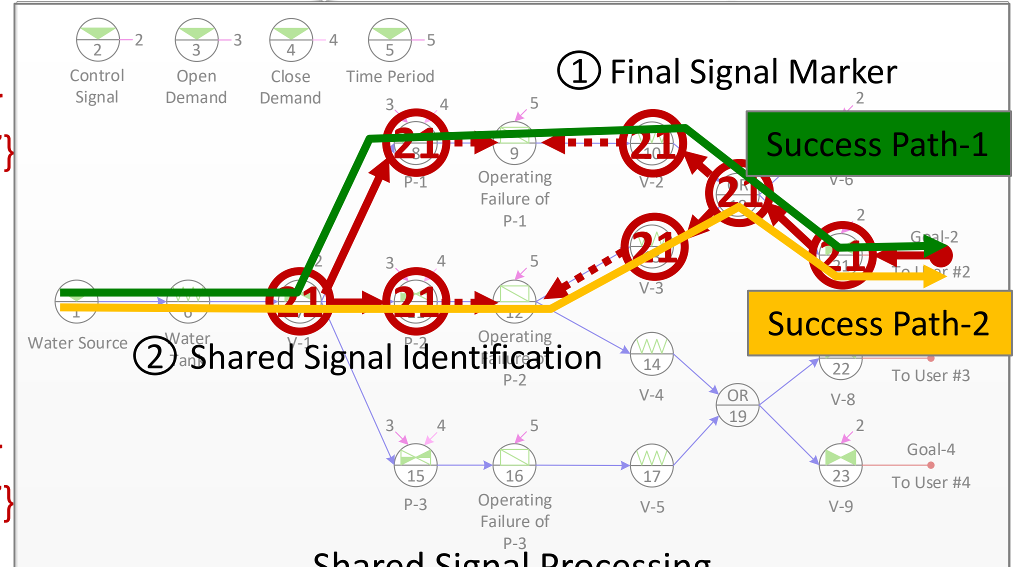
Success Path-2: MPS {1, 6, 7, 11, 12, 13, 21}

P(Success Path-2)=0.9684903

{Water tank with water, Open Valve V-1, Open Pump P-2, Keep P-2 operation for 2 hours, Open Valve V-3, Open Valve V-7}



System Flowchart

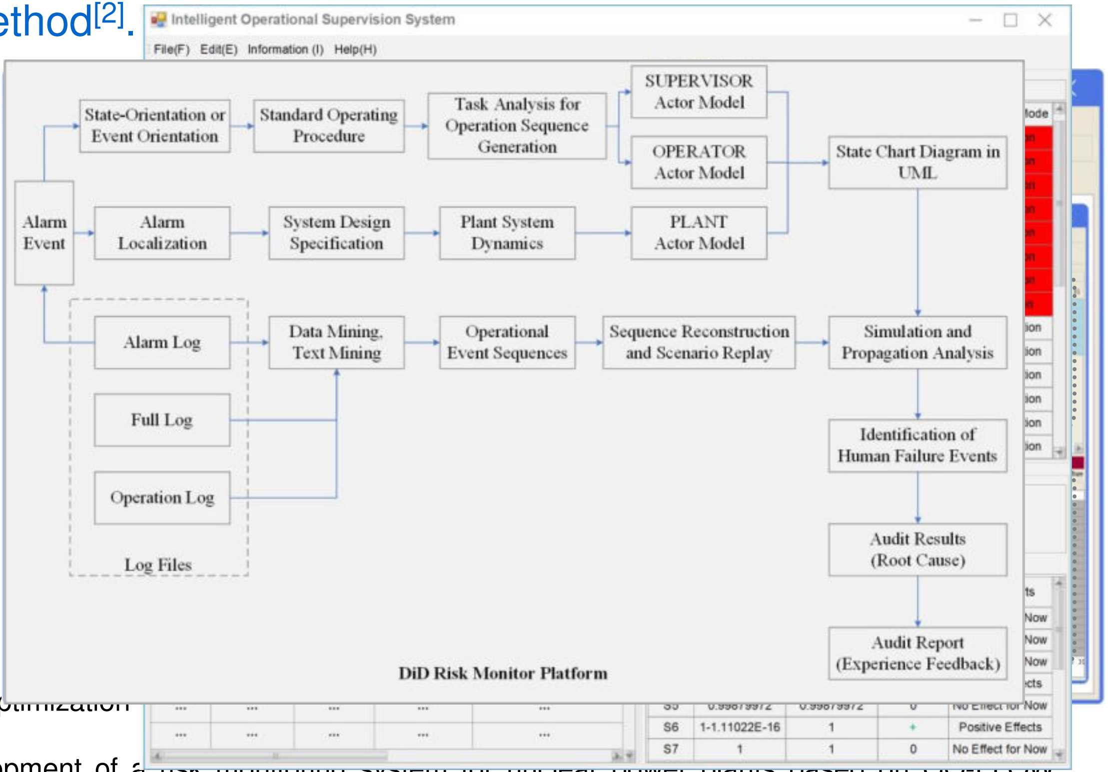


Shared Signal Processing

System GO-FLOW Chart

Enhanced Safety Monitor for Multipurpose Applications

- An enhanced safety monitor is envisioned based on our previous work in risk monitor[3] using the optimized GO-FLOW method[2].
- Existing basic functional modules
  - Equipment Information Management
  - System Configuration Management
  - System Reliability Monitoring
  - Risk Profiler
  - Risk Matrix
- Extended functional modules
  - **Operation Navigation and Supervision**
  - **Human-Centered Safety Audit**



[2] L. C. Zheng, X. Y. Dai, J. Yang, et al. A flexible optimization ... of Nuclear Energy. 156(108200): 1-15, 2020.
[3] J. Yang, M. Yang, H. Yoshikawa, et al., Development of a risk monitoring system for nuclear power plants based on GO-FLOW methodology. Nuclear Engineering and Design. 278: 255–267, 2014.

Conclusions

- An **integration platform boosting with a kernel hybrid compute engine** of DDET, Markov/CCMT and GO-FLOW is presented for dynamic reliability, risk and safety management of nuclear power plants.
- The **DDET models and planning algorithm** implemented based on sequence diagram refactoring and graph-based search can be consistently linked to the dynamic evolution of accident sequence that is coupled with system failures in time series in Living PSA context.
- The **versatile Markov/CCMT solver** is capable of multi-directional search analysis such as forward search, backtracking and high-efficiency bidirectional implementation with analytic applications covering dynamic reliability quantification, risk significant scenario identification, fault localization and system state propagation analysis, etc. of digital process control systems.
- The **interactive path tracing and planning analysis by GO-FLOW** can be further employed in accident investigation and decision-making support for emergency preparedness and response.

Outlook

- Our future work will be focusing on:

  (1) Dynamically interfacing with synchronous simulations for real-time risk scenarios development. The algorithm for DDET model generation and analysis proposed in the study is more of a conceptual framework that works pretty well for random sequence of events under deterministic state transition diagrams. The random event sequences progress under non-deterministic and uncertainty environments will be focused by linking the learning algorithm to synchronous simulation.

  (2) Procedural generation of success paths for emergency decision-making support. The success paths derived from combinatorial minimal path sets at present stage are leapfrogging over procedural content generation and directly linked to goal achievement. More actionable information such as task timing, temporal correlations to group events in minimal path sets will be considered to promote the task scheduling and turn event clustering into actionable steps.

Thank you for your time and attention!