Interim Project Report

Research on the key technologies for intelligent risk-informed decision support system for nuclear safety and emergency response management

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Background Introduction

Project Title: *Research on the key technologies for intelligent risk-informed decision support system for nuclear safety and emergency response management*

Project Duration (2 years): 2022/1/1~2023/12/30

The Contents of Cooperation	
Sub-topic I	Study on a system flow monitoring based Living PSA modeling and assimilation method for predictive risk-oriented intelligence
Sub-topic II	Study on a graph and state space based fast dynamic reliability and risk compute engine
Sub-topic III	Study on task and success path planning under extreme environmental and accident conditions
Sub-topic IV	Development of an integrated decision support system for risk-oriented intelligent applications

Background Introduction

Project Participants and Task Cooperation

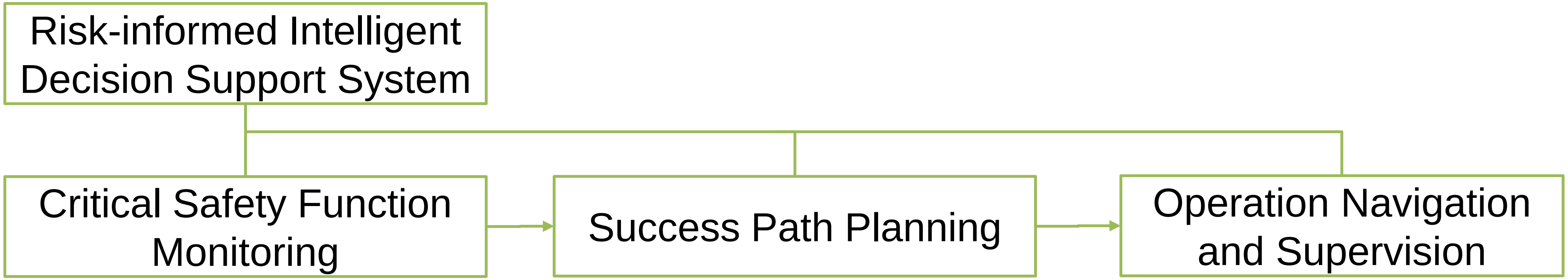
Organizations	Representatives	Task Cooperation	
Non-profit Organization Symbio Community Forum (Japan)	Prof. Hidekazu Yoshikawa	1. Risk layering for safety supervisory and management	4. Jointly organize an international workshop on operational safety and emergency response planning management in NPPs. 5. Participate in and report the research progress in annal general meeting.
Utsunomiya University (Japan)	Prof. Takeshi Matsuoka	2. An enhanced modeling and analysis platform to be developed for dynamic reliability and risk analysis	
Shenzhen University (China)	Prof. Ming Yang	3. Success path planning for emergency response management in the early stage of accident mitigation and recovery.	
South China University of Technology (China)	Dr. Jun Yang	Overall task implementation and coordination	

Research Objectives

Criteria for Project Completion

Type of outputs	Requirements	Completed Inspection
Patent application	1	**2**
Talents cultivation	6	**Undergoing**
International PCT (Patent Cooperation Treaty) application	1	**2**
Software copyright registration	1	**1**
Papers	8 (SCI: 4; EI: 4)	SCI: **2**; EI: 4
Technical report	1	**To be completed at the end of the project**
International workshop	1	**To be held in July**
Annual Meeting	≥2	**2**+**1**(**To be held in November**)

Part I: Risk layering for safety supervisory and management



◻ Intelligent Risk-informed Decision Support System

The intelligent risk-informed decision support system aims to implement, integrate and maintain success paths to hazard mitigation with planning efforts for risk-layering safety supervisory and management. The intelligent risk-informed decision support system consists of three parts: i) *critical safety function monitoring*; ii) *success path planning*; iii) *operation navigation and supervision*.

Critical safety function monitoring: provide an overview of the safety status of the plant.

Success path planning: provide countermeasures to unexpected events under extreme conditions.

Operation navigation and supervision: provide procedural guidance to operators for efficient task execution and in-process human interaction supervisory.

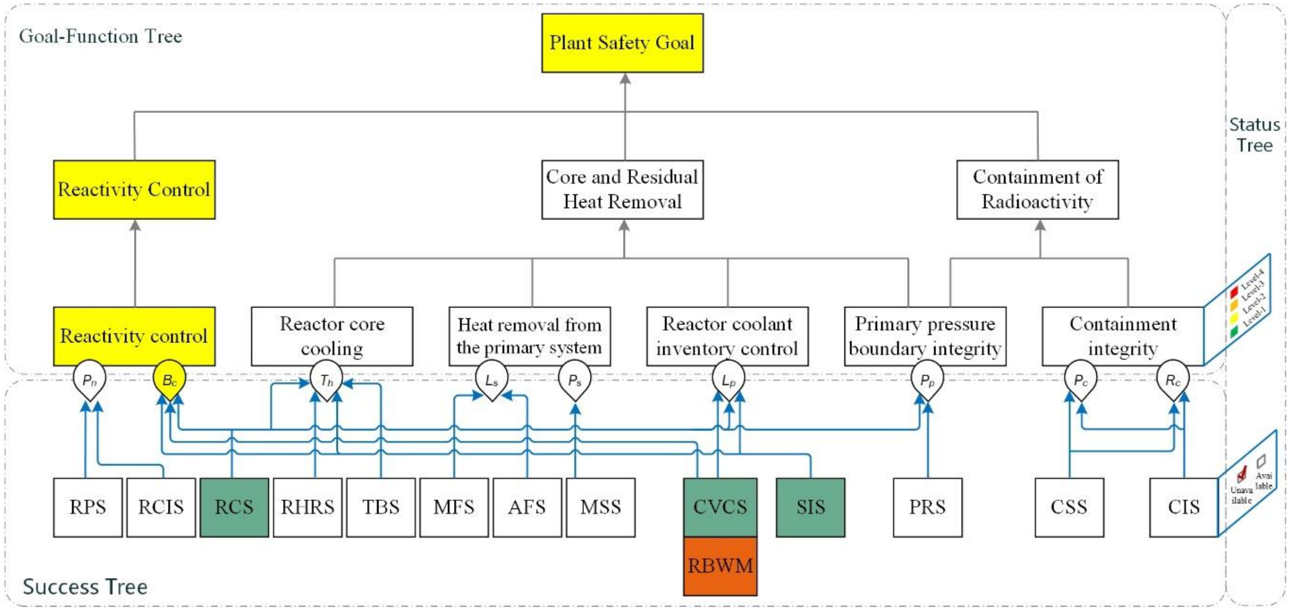
Part I: Risk layering for safety supervisory and management

◻ Critical Safety Function Monitoring

The Critical Safety Function (CSF) monitoring subsystem is designed to be consistent with the Safety Parameter Display System (SPDS) and the Intelligent Alarm System design in nuclear power plants.

The CSF monitoring system is developed using a deep knowledge approach, where complex engineering system domain knowledge is represented by **the coupled goal-function tree, success tree, and state tree models**.

- *Goal-function tree: decomposition of Goals-Functions.*
- *Success tree: means (process and success paths) to realize functions.*
- *State tree: status of CSF and systems components.*



Coupling tree model for knowledge representation

The nuclear safety goal can be achieved and safeguarded by the following 6 critical safety functions:

1. *Reactivity control*
2. *Reactor core cooling*
3. *Heat removal from the primary system*
4. *Reactor coolant inventory control*
5. *Primary pressure boundary integrity*
6. *Containment integrity*

Part I: Risk layering for safety supervisory and management

□ Critical Safety Function Monitoring

How to evaluate the overall plant safety status especially from a risk perspective?

Possible solutions:

Solution #1 (State Combination Method)	Solution #2 (Conservative Method)	Solution #3 (Risk Priority Number)
The evaluation of the overall plant safety status is regarded as a multi-valued function that all possible combinations of the states of six critical safety functions should be considered.	The state of nuclear safety goal is simply determined based on the most damaged state of critical safety functions.	The overall plant safety status is evaluated from a risk perspective by using the Risk Priority Number (RPN) methodology.
✓ State of being self-evident ǂ State space is huge. ǂ Lack of guiding principles of risk management	✓ Simple to implement. ǂ The state definition is not refined enough.	✓ Has a solid theoretical foundation and widely used. ǂ May not reflect the actual risk.

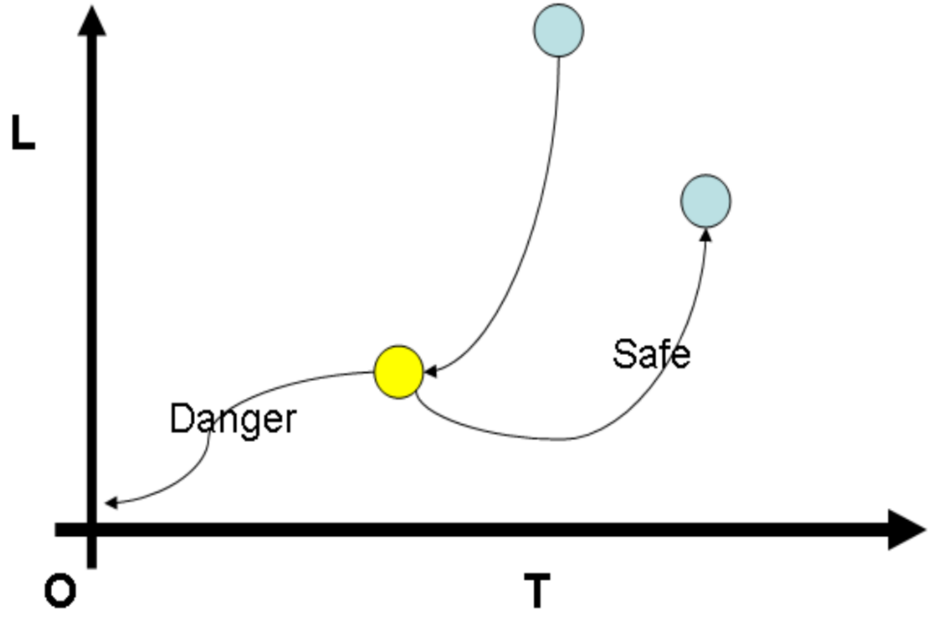
Part I: Risk layering for safety supervisory and management

Critical Safety Function Monitoring

Try it!

Another way: to integrate the CSF monitoring with multi-valued state definition into Defense-in-Depth (DiD) risk monitor.

Risk level	Stop	Cool	Contain	Possibility of severe accident
0	1	1	1	No risk Safely shutdown, cooled and no release
1	1	1	0	No severe accident phenomena but some problem in containment
2	1	0	1	Loss of not so serious cooling function Safely shutdown, but cooling failed but no release
3	1	0	0	Serious severe accident possible Safely shutdown, but both cooling and contain function failed
3	0	1	1	Severe accident may be suppressed by ESF function Shutdown failed but cooling and no release
3	0	1	0	Some contain function failed Shutdown failed , cooled but released
4	0	0	1	Serious though severe accident phenomena occurr because containment function succeeded Shutdown failed , cooling failed but no release
5	0	0	0	Worst severe accident because all safety functions failed



How should we configure the risk level ranking when the risk level is related to the state combinations of 6 safety critical functions with multi-valued state definition?

Part II: Development of an enhanced modeling and analysis platform

■ Retrofitting of GO-FLOW Method

☑ **An automated GO-FLOW modeling tool:** to be developed in support of *reliability-based system engineering design* and *reliability/risk monitor applications.*

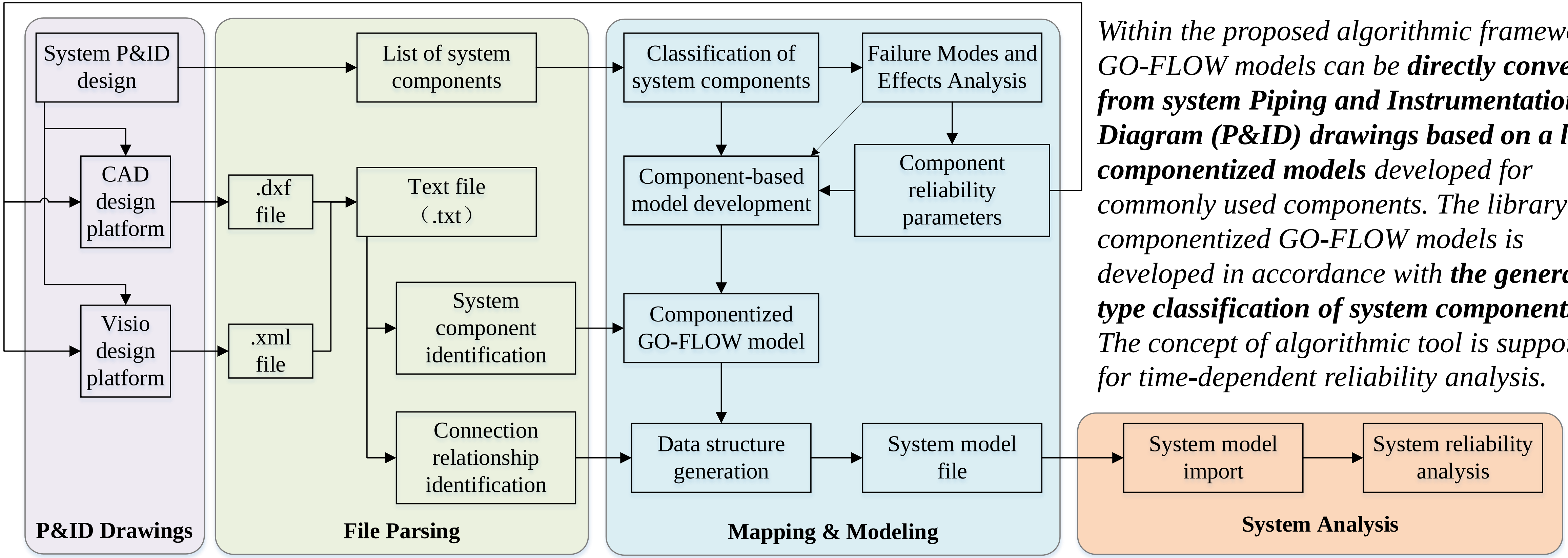
☑ **An enhanced GO-FLOW analysis algorithm**: to be developed to expand the capabilities of *exact calculation* and the *minimum path sets interpretation*.

☒ **Expansion and Optimization of GO-FLOW platform**: *reliability analysis of repairable PMS system*, *integration of common cause failure/importance analysis/sensitivity analysis*, *Visual presentation of results*.

Part II: Development of an enhanced modeling and analysis platform

☑ II-1: An automated GO-FLOW modeling tool (talked by Mr. He Zhanyu)

The procedure implemented for automated GO-FLOW modeling can be divided into three main steps: i) system P&ID design information extraction and analysis; ii) connection relationship identification; iii) GO-FLOW model generation.



*Within the proposed algorithmic framework, GO-FLOW models can be **directly converted from system Piping and Instrumentation Diagram (P&ID) drawings based on a list of componentized models** developed for commonly used components. The library of componentized GO-FLOW models is developed in accordance with **the general type classification of system components**. The concept of algorithmic tool is supportive for time-dependent reliability analysis.*

Part II: Development of an enhanced modeling and analysis platform

☑ II-2: An enhanced GO-FLOW analysis algorithm

The algorithm is implemented by the following steps:

Step-1: GO-FLOW modeling.

Step-2: Final signal marking.

Step-3: Shared signal identification.

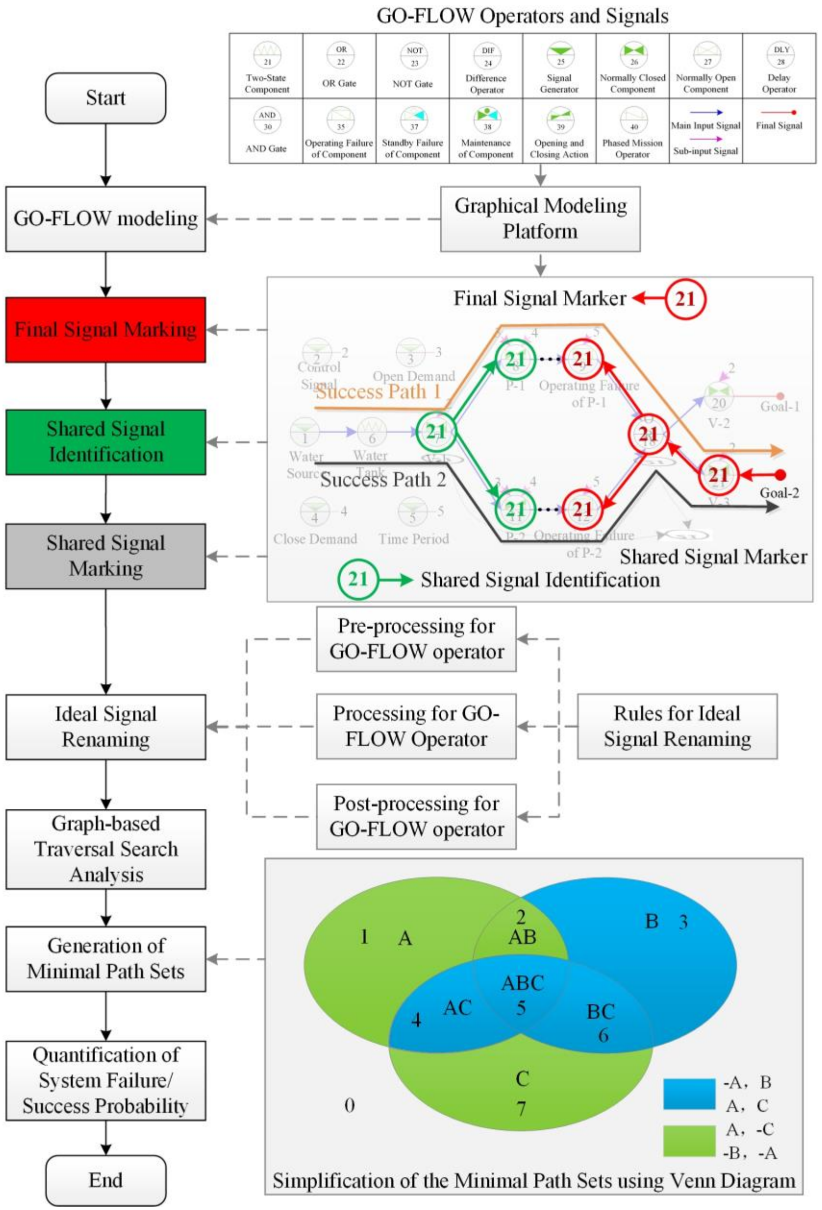
Step-4: Shared signal marking.

Step-5: Ideal signal renaming.

Step-6: Graph-based traversal search analysis.

Step-7: Generation of the minimal path sets.

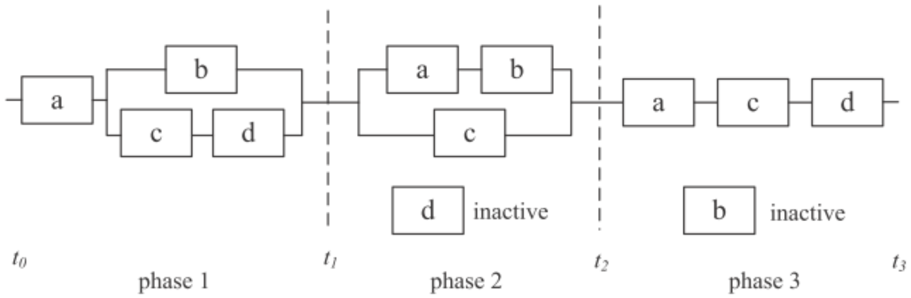
Step-8: Quantification of system failure/success probability.



Part II: Development of an enhanced modeling and analysis platform

☒ II-3: Expansion and Optimization of GO-FLOW Platform

(1) *Reliability analysis of repairable PMS system*

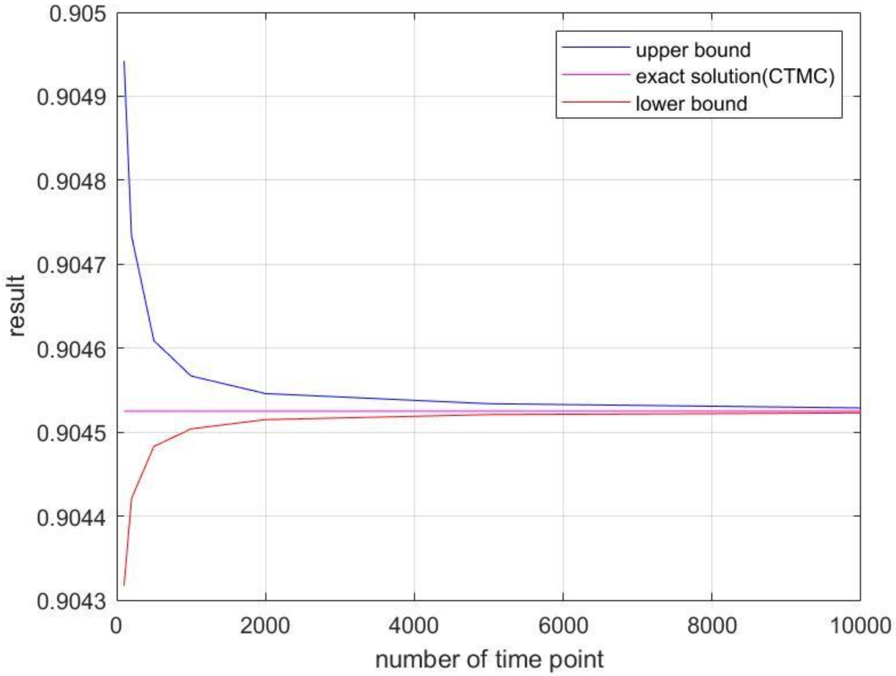


Essential problems to be solved:

① Exact solution of availability of repairable PMS system (Continuous-Time Markov Chain, CTMC)

② Balance efficiency, accuracy, and flexibility in system reliability/availability calculation. (GO-FLOW/Markov chain with flexible time point interpolation)

③ Obtain margin of error, confidence interval, confidence level.

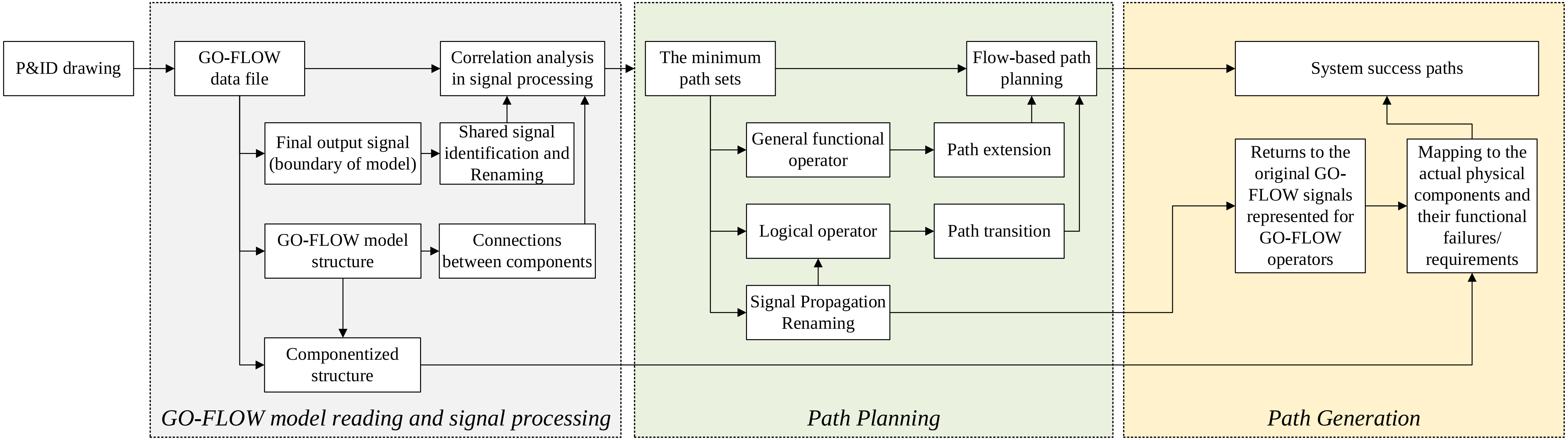


Part III: Success Path Planning for Emergency Response Management

☑ III-1: Success Path Planning based on Minimum Path Sets (MPSs)

The success path tracing and planning algorithm is implemented based on the inputs of complete set of ***minimal path sets*** that are obtained using graph traversal analysis on the GO-FLOW chart.

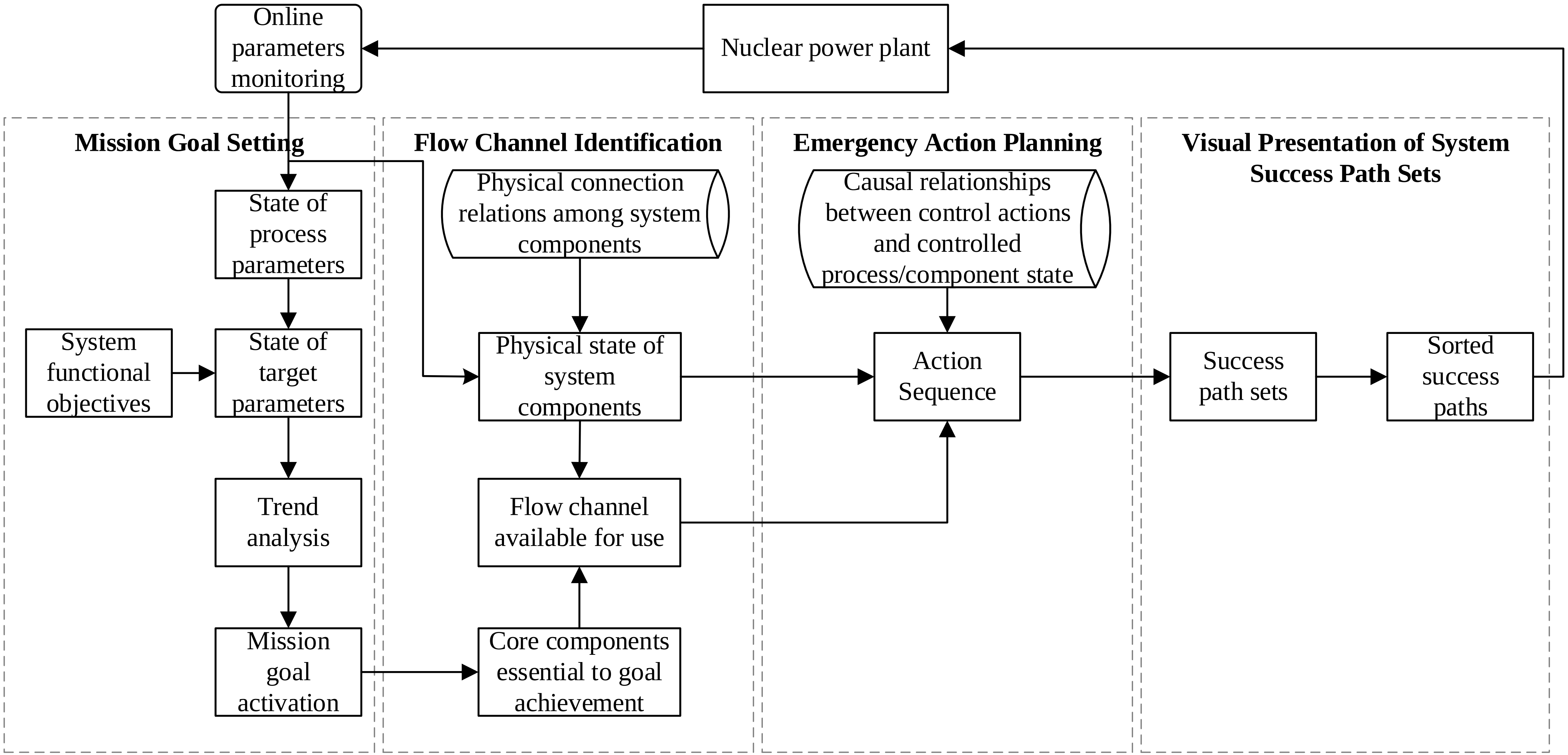
It should be noted that the success paths converted from minimal path sets can only provide **procedural guidance from the perspective of function realization and goal achievement in a high level of abstraction**. The needs of step-by-step guide in temporal sequence are also considered with the sequential flow of signals, process simulation as well as practical engineering experiences in our ongoing studies.



Part III: Success Path Planning for Emergency Response Management

☑ III-2: Success Path Planning based on Knowledge Representation and Reasoning

- A Flow-based Success Path Planning Method

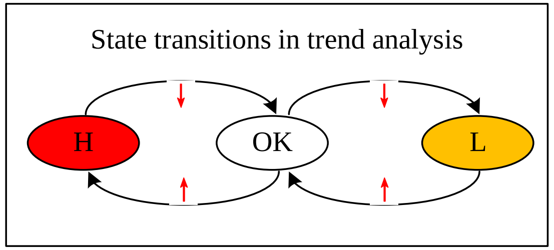


Part III: Success Path Planning for Emergency Response Management

☑ III-2: Success Path Planning based on Knowledge Representation and Reasoning

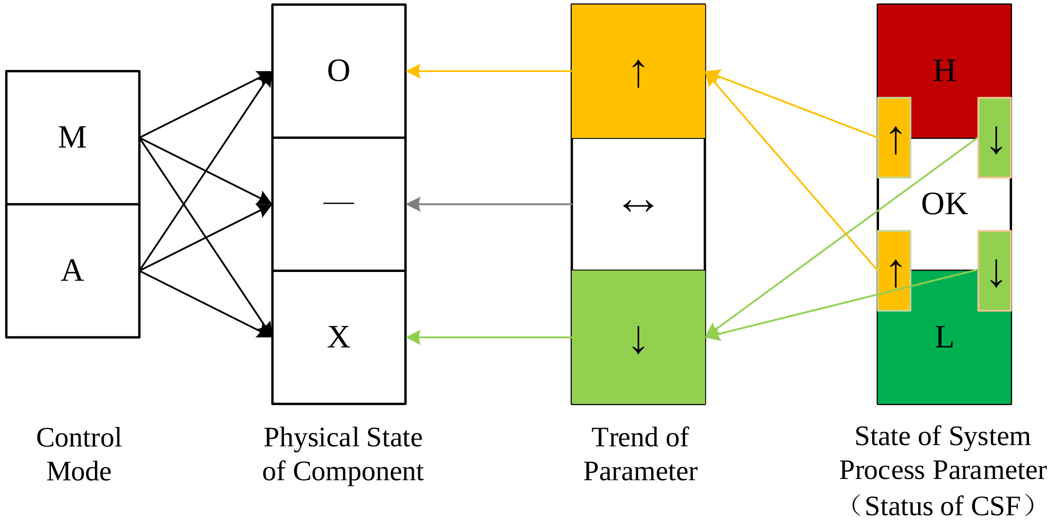
➤ A Flow-based Success Path Planning Method

The flow-based success path planning is implemented with goal- and function-oriented task & action planning. The mission goal is determined based on system functional objectives and online monitoring of key process parameters. The emergency action planning is carried out by ***deductive reasoning with anti-degradation goals and objectives in a reversed logical value setting***.



Category	Component	Diagram	Functions of Components	Physical State of Component	Causal Relations between Process Variables	Control Mode	Causality in Actions
Tanks/Containers	Water Tank		Source Function; NIMO; Satisfy: $F_{out}=dV/dt$	Physical states: good/broken; Parameters: Water level; Function states: H-OK-L	F_{out} → Volume: H→L, OK→OK, L→H	Non-action Component	
			Storage Function; MIMO; Satisfy: $\Sigma F_{out} - \Sigma F_{in} = dV/dt$	Physical states: good/broken; Parameters: Water level; Function states: H-OK-L	F_{in} → Volume: H→H, OK→OK, L→L; F_{out} → Volume: H→L, OK→OK, L→H	Non-action Component	
Pumps	Centrifugal Pump		Transport Function; SISO; Satisfy: $F_{out}=F_{in}$	Physical states: Open/Close; Parameters: Flowrate; Function states: H-OK-L	F_{in} → F_{out}: H→H, OK→OK, L→L	Manual/ Automatic	Action → Flowrate: O→↑, X→↓
				Physical states: Full Open/Half Open/Full Close; Parameters: Flowrate; Function states: H-OK-L	F_{in} → F_{out}: H→H, OK→OK, L→L	Manual/ Automatic	Action → Flowrate: O→↑, —→↔, X→↓
Valves	Cut-off Valve		Transport Function; SISO; Satisfy: $F_{out}=F_{in}$	Physical states: Open/Close; Parameters: Flowrate; Function states: H-OK-L	F_{in} → F_{out}: H→H, OK→OK, L→L	Manual/ Automatic	Action → Flowrate: O→↑, X→↓
	Regulating Valve		Transport/Regulating Function; SISO; Satisfy: $F_{out}=F_{in}$	Physical states: Continuous; Parameters: Flowrate; Function states: H-OK-L	F_{in} → F_{out}: H→H, OK→OK, L→L	Manual/ Automatic	Action → Flowrate: O→↑, —→↔, X→↓
	Three-way Valve		Transport/Guiding Function; SITO; Satisfy: $F_{in}=F_{out1}+F_{out2}$	Physical states: Open in Upper/Lower Valve, Close; Parameters: Flowrate; Function states: H-OK-L	F_{in} → F_{out}: H→H, OK→OK, L→L	Manual/ Automatic	Action → Flowrate: O→↑, —→↔, X→↓
	Check Valve		Transport Function; SISO; Satisfy: $F_{out}=F_{in}$	Physical states: On; Parameters: Flowrate; Function states: H-OK-L	F_{in} → F_{out}: H→H, OK→OK, L→L	Non-action Component	
			Barrier Function; SISO; Satisfy: $F_{out}=0$	Physical states: Blockage; Parameters: Flowrate; Function states: H-OK-L	F_{out}: L		
Heat Exchangers	Heat Exchanger		Transport Function; TITO; Satisfy: $F_{in1}=F_{out1}$ $F_{in2}=F_{out2}$	Physical states: Good/Broken; Parameters: Temperature; Function states: H-OK-L	F_{in} → F_{out}: H→H, OK→OK, L→L	Non-action Component	

Knowledge Representation



Physical state of component	**Trend of parameter**	**State of process parameter**
O： Turn on/Turn up	↑ ： Uptrend	H： High-value alarm
—： Maintain current state/position	↔ ： No change	OK： Within normal range
X： Turn off/Turn down	↓ ： Downtrend	L： Low-value alarm

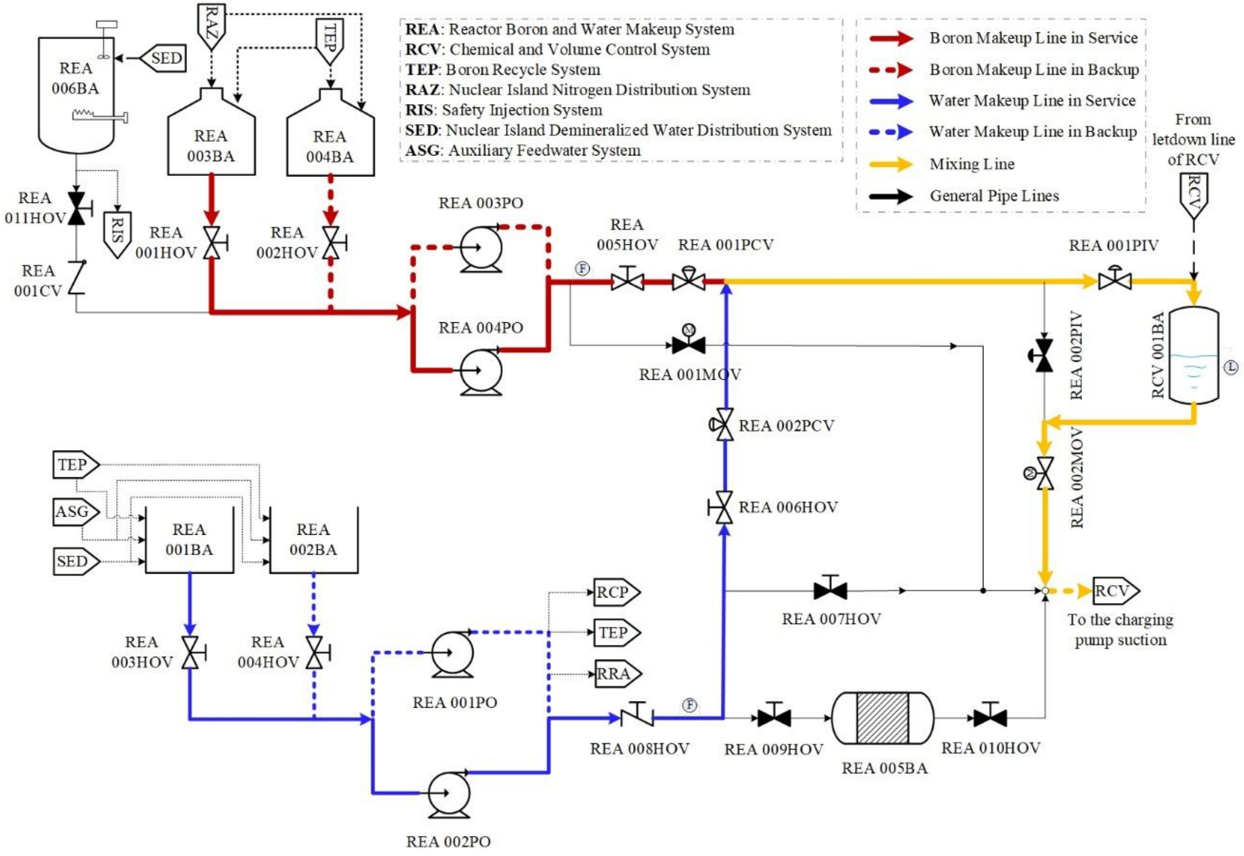
Backward causation

Part III: Success Path Planning for Emergency Response Management

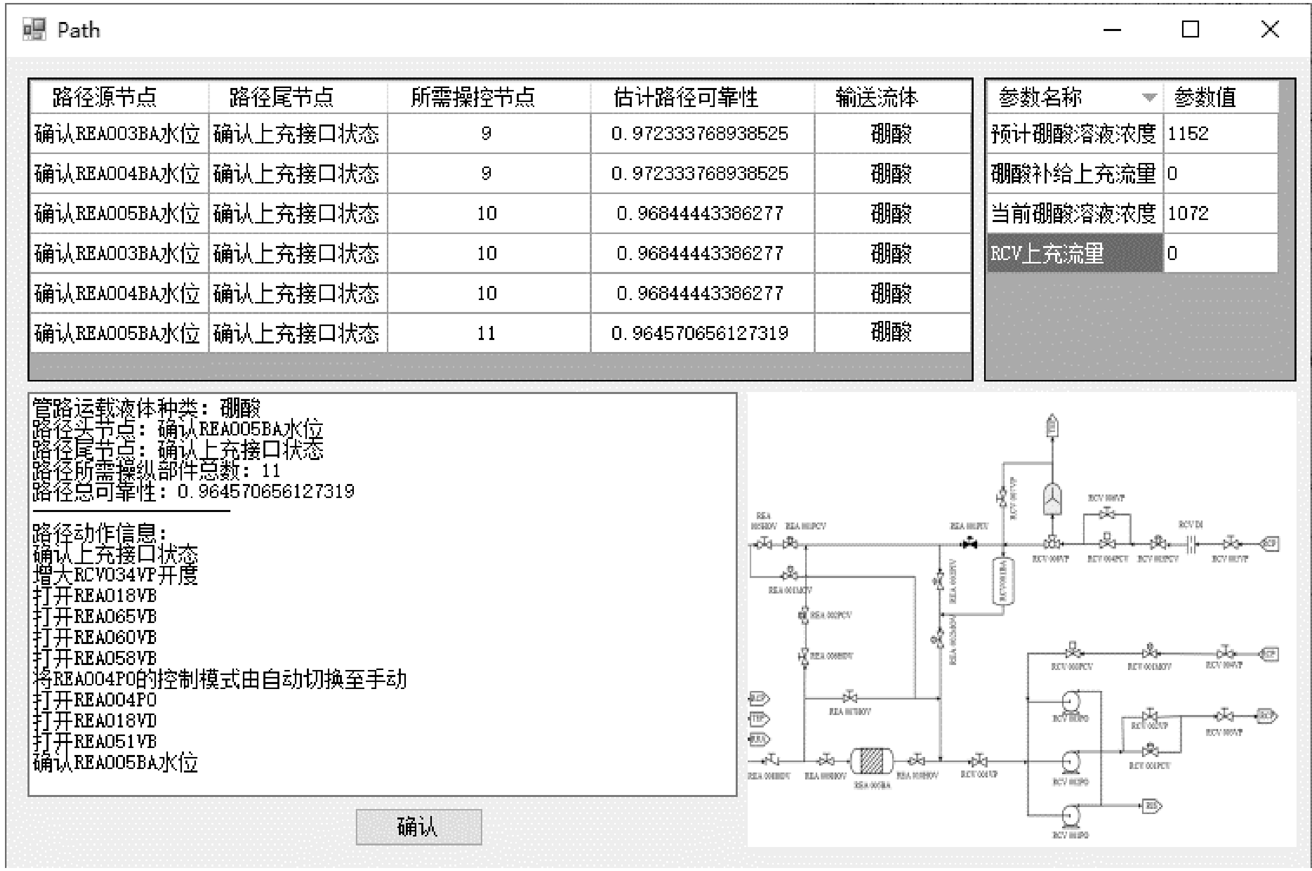
☑ III-2: Success Path Planning based on Knowledge Representation and Reasoning

- A Flow-based Success Path Planning Method

Case Study: Manual Makeup in slight boron dilution accident



Example REA system



路径源节点	路径尾节点	所需操控节点	估计路径可靠性	输送流体
确认REA003BA水位	确认上充接口状态	9	0.972333768938525	硼酸
确认REA004BA水位	确认上充接口状态	9	0.972333768938525	硼酸
确认REA005BA水位	确认上充接口状态	10	0.96844443386277	硼酸
确认REA003BA水位	确认上充接口状态	10	0.96844443386277	硼酸
确认REA004BA水位	确认上充接口状态	10	0.96844443386277	硼酸
确认REA005BA水位	确认上充接口状态	11	0.964570656127319	硼酸

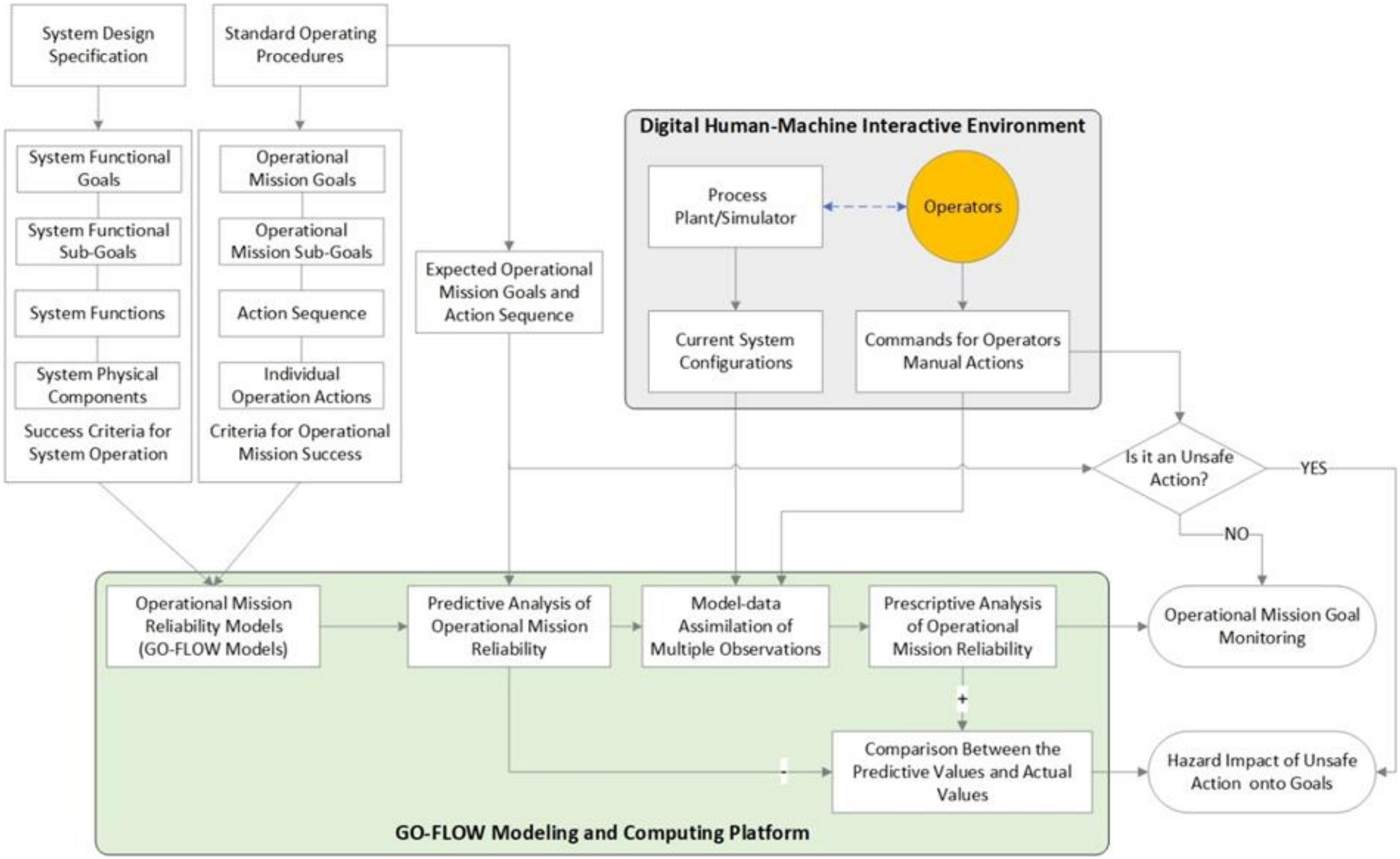
参数名称	参数值
预计硼酸溶液浓度	1152
硼酸补给上充流量	0
当前硼酸溶液浓度	1072
RCV上充流量	0

Success Path Sets

Part IV: Operation Navigation and Supervision

☑ Operational Mission Reliability Analysis and Monitoring

- The operational mission reliability analysis and monitoring involves ***system GO-FLOW modeling***, ***tread impact analysis*** based on synchronous prediction and supervision and ***reliability profiler for goal monitoring***.
- The monitoring of operational mission goals using measures of ***instantaneous reliability*** pays more attention to the continuous real-time sensing with system configuration changes involved with in-process human interactions during the execution of a task.



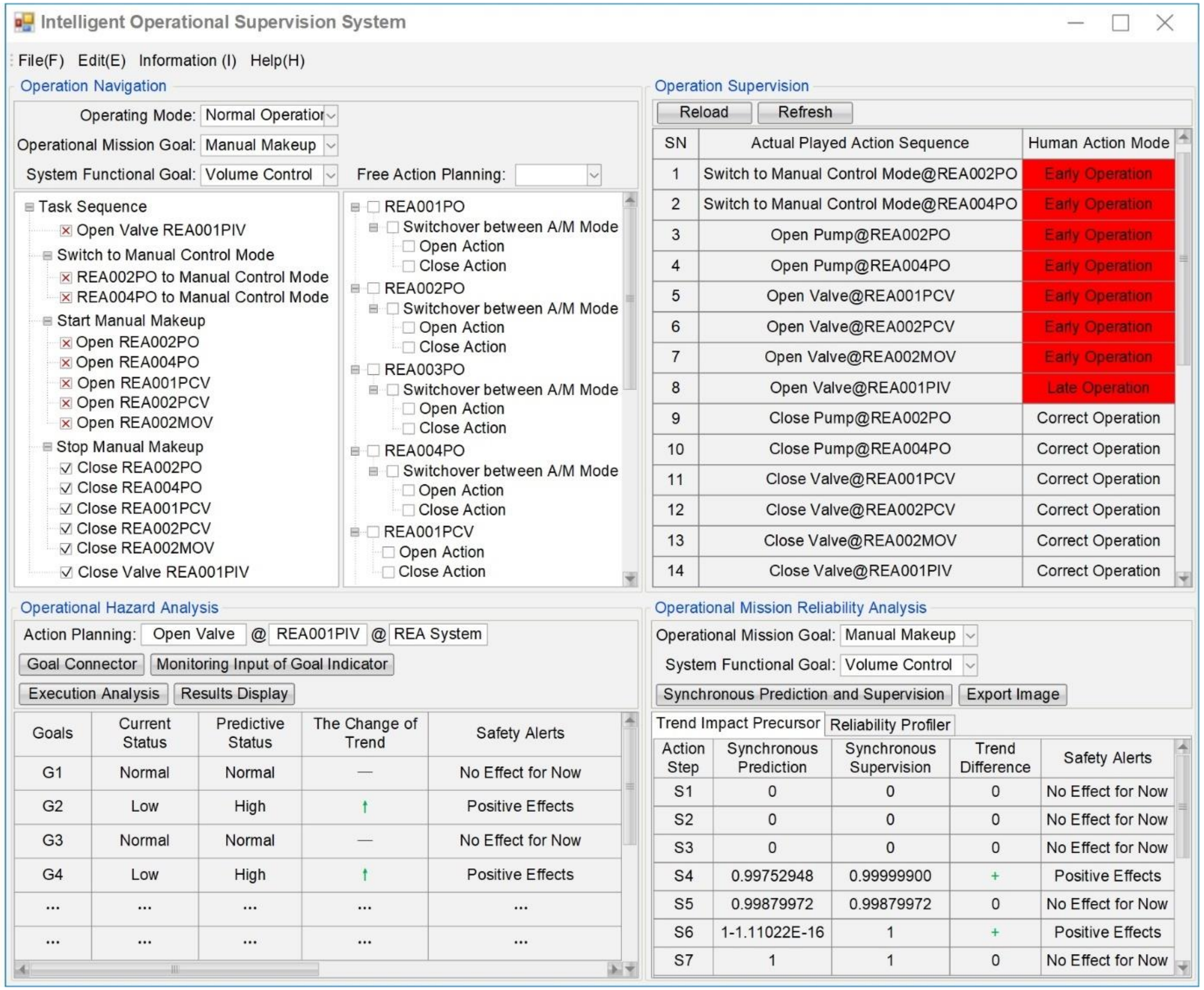
GO-FLOW modeling and analysis process for operational mission reliability analysis

Part IV: Operation Navigation and Supervision

□ Intelligent Operational Supervision System

An intelligent operational supervision system is about to be powered with the integration of following capabilities.

- Unsafe Action Identification (Pattern-based Recognition)
- Procedure-based Navigation and Supervision
- Non-procedural Path Guiding
- Operational Mission Reliability Monitoring
- Trend Impact Prediction
- Operational Hazard Analysis



Thank you for your attention.