Cognitive-Based State Diagnosis Module for Operator Decision Support in Nuclear Power Plants

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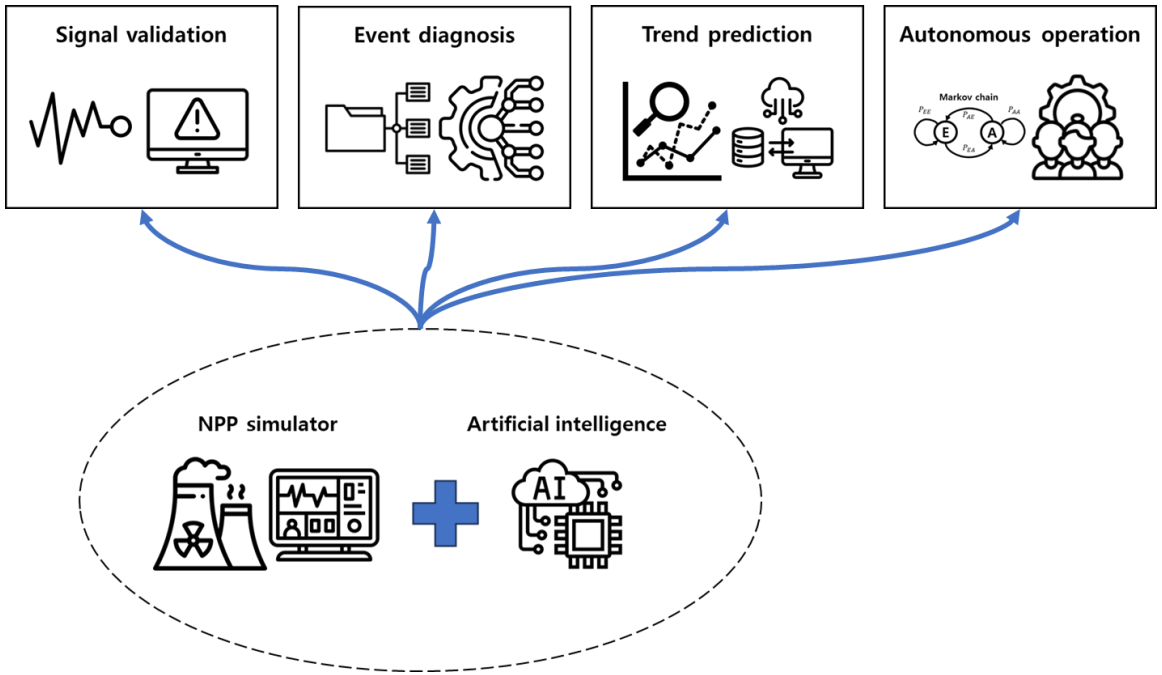
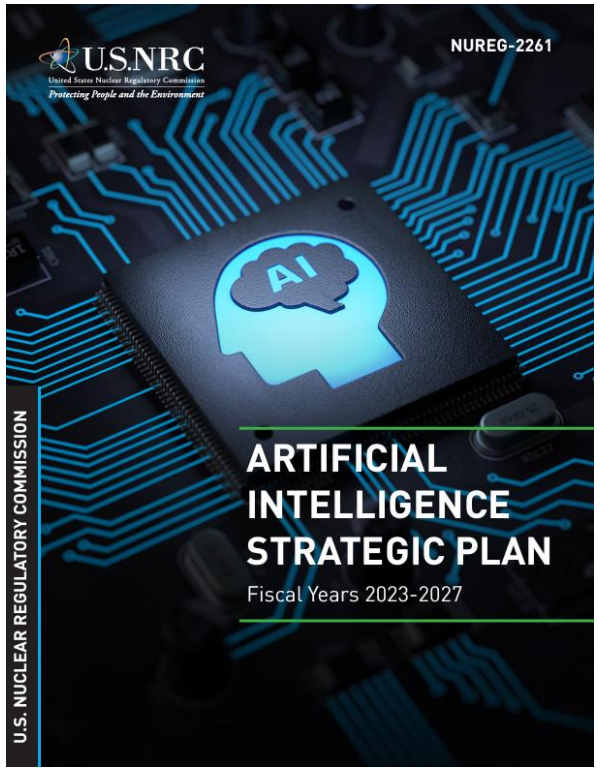
01 Introduction

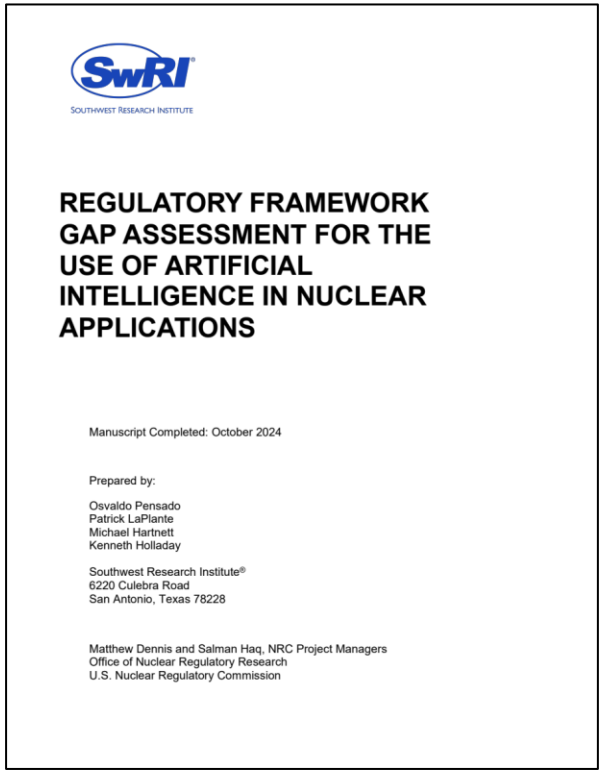
SAPHE

AI research in the nuclear engineering fields

- Big data + Computing power + AI algorithm → AI research in nuclear engineering fields
- Artificial Intelligence Strategic Plan 2023-2027 (NUREG-2261)
- Regulatory Framework Gap Assessment for the Use of AI in Nuclear Applications



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REGULATORY FRAMEWORK GAP ASSESSMENT FOR THE USE OF ARTIFICIAL INTELLIGENCE IN NUCLEAR APPLICATIONS

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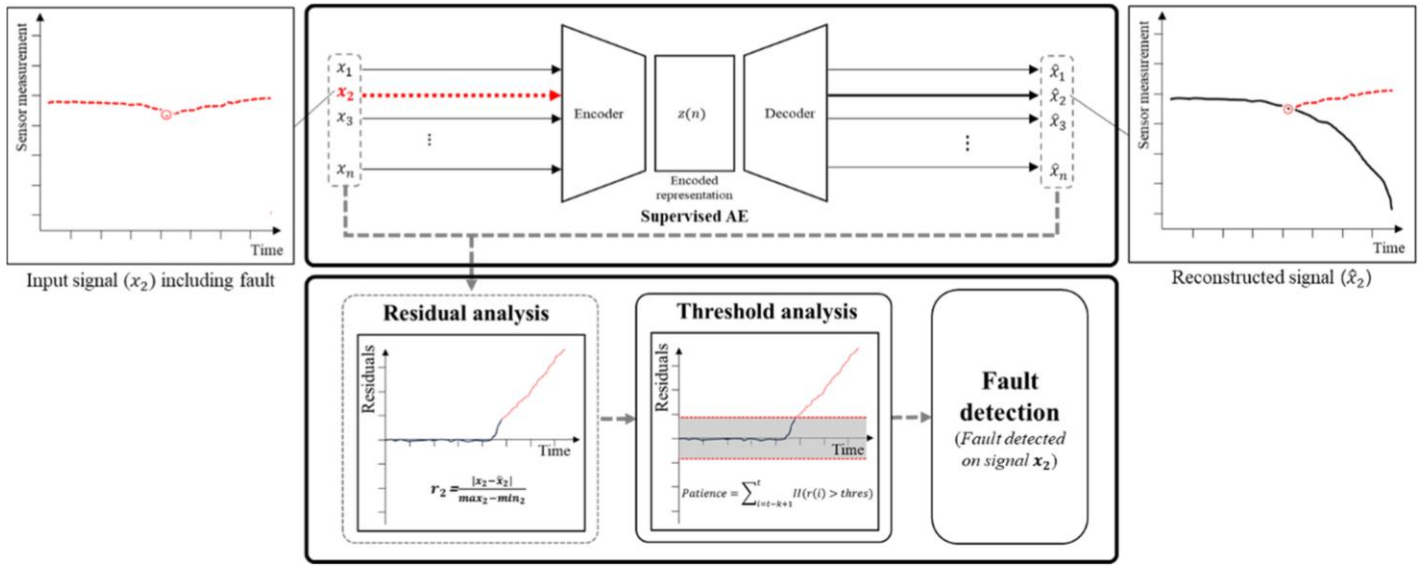
Introduction

Motivation for AI-Based Operator Support in NPPs

Extensive research on AI-based operator decision support algorithms

- **Signal validation algorithm**
  - ✓ Detection and correction of unreliable sensor signals
- State diagnosis algorithm
  - ✓ Identification of current plant conditions and eXplainable AI (XAI) results
- Progression prediction algorithm
  - ✓ Prediction of future plant state changes

1) Signal validation algorithm



1) Choi, J., Koo, S. R., & Lee, S. J. (2026). Sensor fault detection and signal restoration using scenario-guided supervised autoencoders for nuclear power plant accidents. Progress in Nuclear Energy, 196, 106374.

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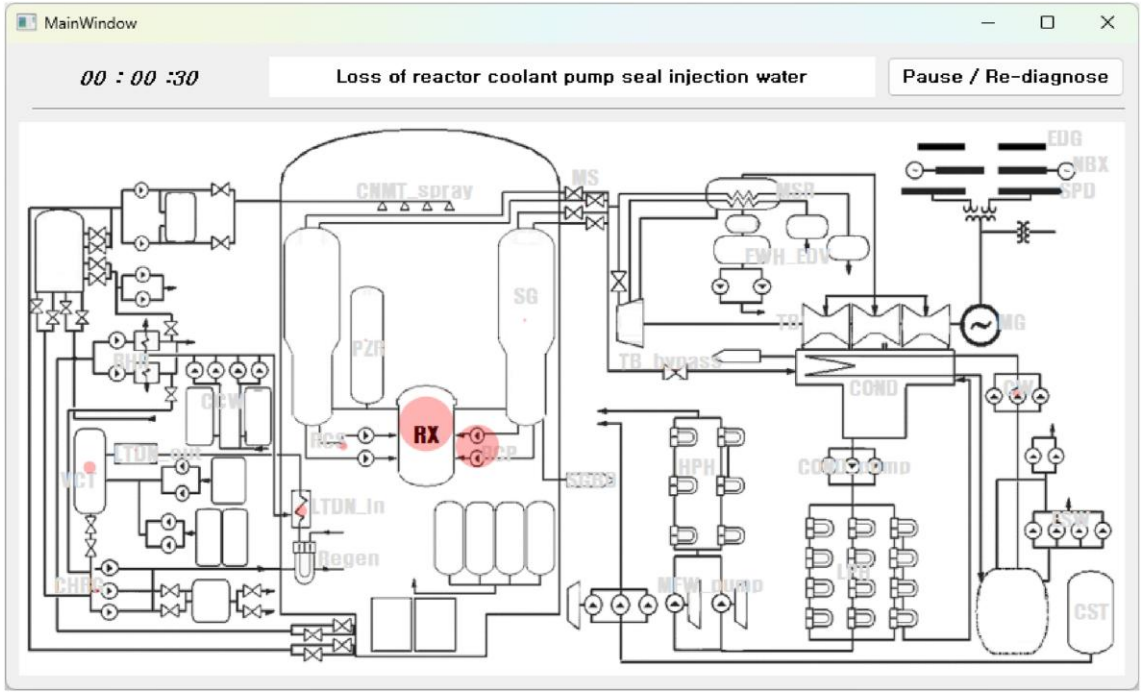
[2] State diagnosis algorithm



2) Shin, J. H., Kang, J. S., Kim, J. M., & Lee, S. J. (2025). Concept of understandable diagnostic cause visualization with explainable AI and multilevel flow modeling. Nuclear Engineering and Technology, 57(8), 103589.

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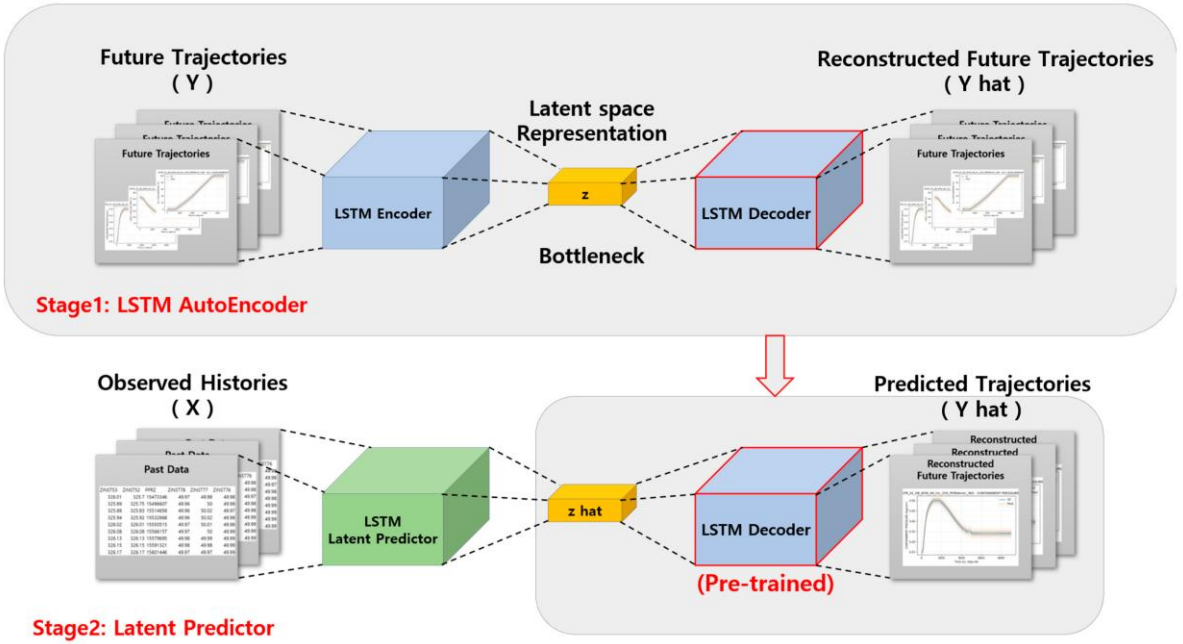
3) Progression prediction algorithm



3) Jung, D., Bae, J., Kang, H. G., & Lee, S. J. (2026). Latent Trajectory Forecasting for Long-Horizon Multivariate Nuclear Power Plant Parameter Prediction. Energies, 19(13), 3048.

Cognitive-based organization of AI-derived information for state diagnosis

- Signal validation algorithm
  - ✓ **Can the observed symptoms be trusted?**
- State diagnosis algorithm
  - ✓ **What abnormal state is most likely?**
- Progression prediction algorithm
  - ✓ **How urgent is the current situation?**

What information do I need to diagnose the current situation?

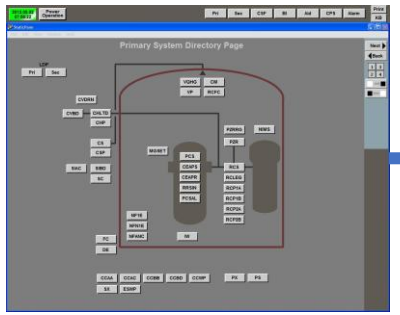
❖ Need for cognitive-based state diagnosis module design for operator decision support

02 Method

Objective

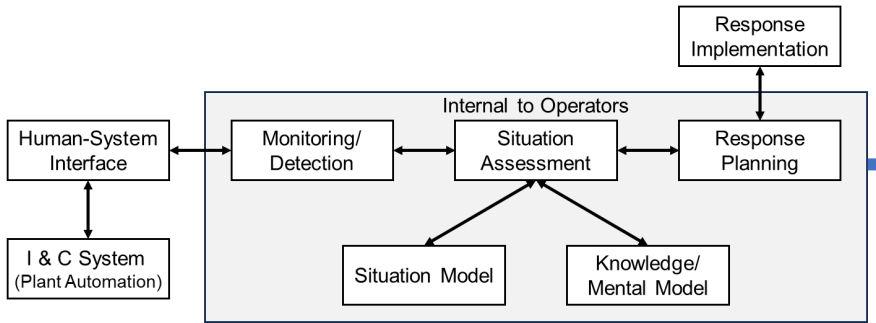
- Design a cognitive-based state diagnosis HSI (Human-System Interface) module for operator decision support during abnormal conditions in the main control room

MCR Operator HSI Design Philosophy



Cognitive-based state diagnosis module

Cognitive-based state HSI design



Objective

- Design a cognitive-based state diagnosis HSI (Human-System Interface) module for operator decision support during abnormal conditions in the main control room

Cognitive-based design framework

1. Operator cognitive process analysis
   - How operators recognize and assess abnormal situations

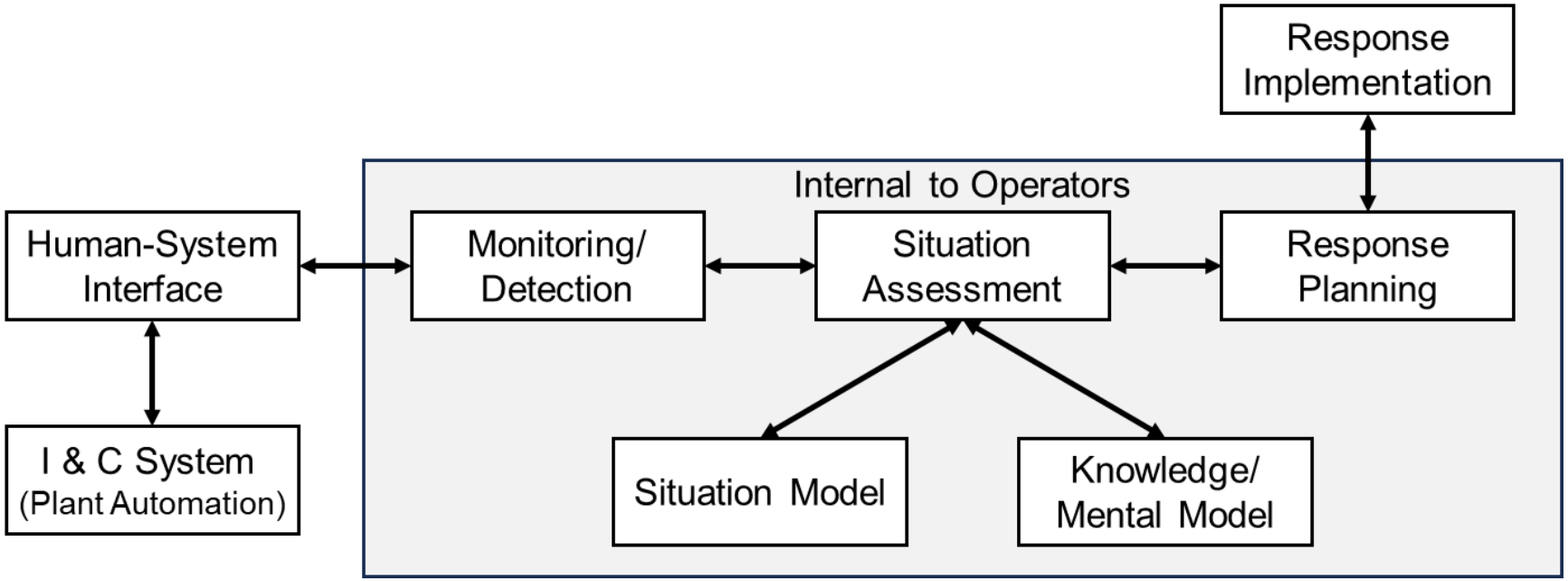
2. Information requirement derivation
   - What information is needed for state diagnosis

3. Information structure design
   - How diagnostic information should be organized for operator decision support

Operator cognitive process in abnormal situations

- A Technique for Human Error Analysis (ATHEANA)
  - Monitoring / detection: Recognition of abnormal symptoms
  - Situation assessment: Interpretation of plant state
  - Response planning: Selection of response strategy
  - Response implementation: Execution of operator actions

[4] Cognitive activities of NPP operators during abnormal situations



4) U.S. Nuclear Regulatory Commission. (2000). Technical basis and implementation guidelines for a technique for human event analysis (ATHEANA) (NUREG-1624, Rev. 1).

Diagnostic information requirements for state diagnosis

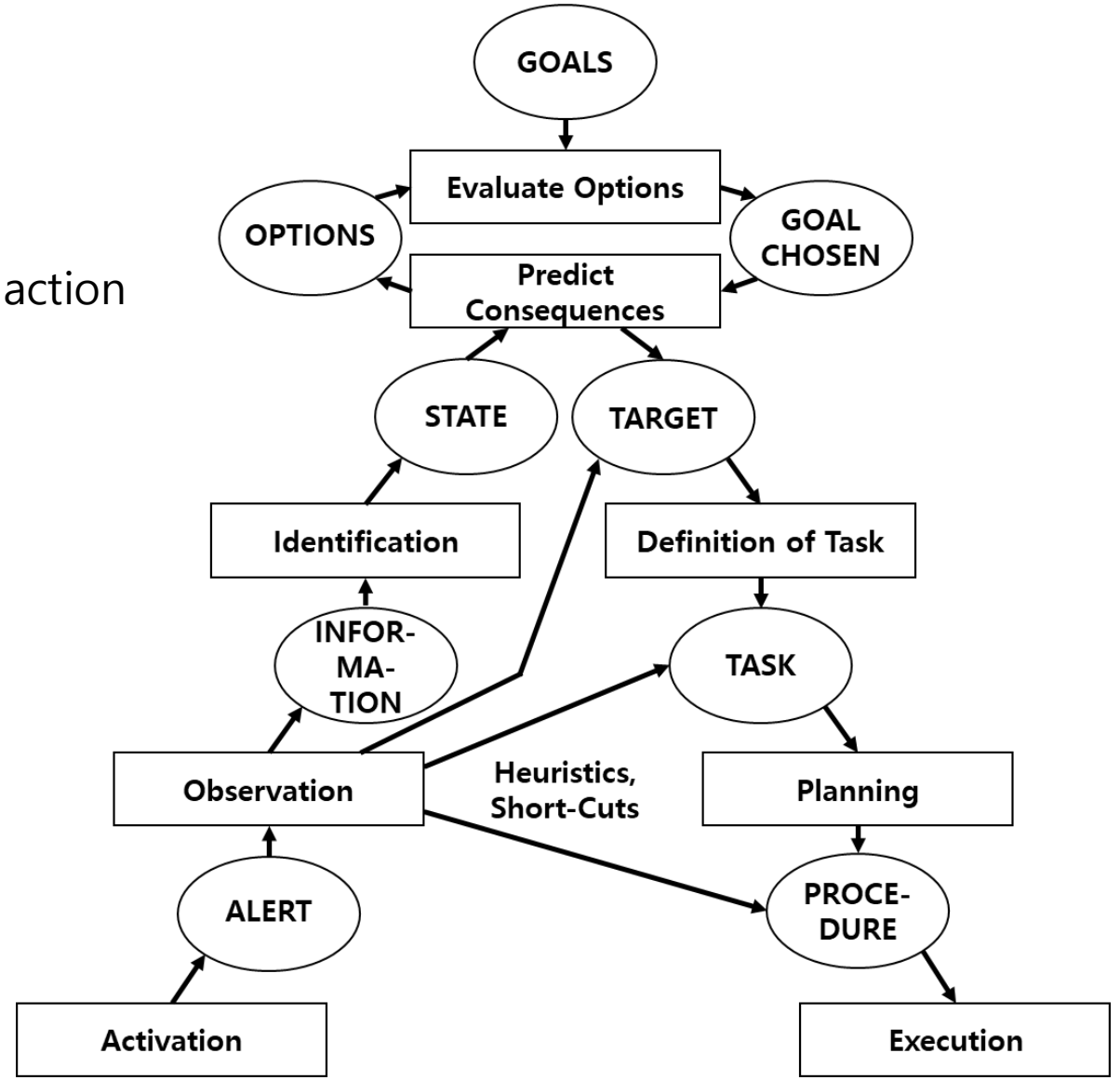
Cognitive activity	Potential human error	Required diagnostic information
Monitoring / detection	Missing critical alarms or misjudging faulty sensor signals	Alert, signal validation, procedure entry-condition satisfaction
Situation assessment	Confusing the cause of an abnormal event	Diagnostic results, diagnostic reasons
Response planning	Delayed response due to misjudging available time	Trip margin time, key-variable trend prediction
Response implementation	Procedure omission, wrong manipulation, or delayed action	Procedure/action support

- Required diagnostic information was derived from potential human errors in each cognitive activity.

Decision ladder for diagnostic reasoning

- Basic information processes in a decision task
- Transitions between cognitive states
- Situation analysis → goal evaluation → planning → action
  - □ Rectangles: Cognitive activity
  - ○ Ovals: State of knowledge

5) Decision ladder



5) Rasmussen, J. (1993). Diagnostic reasoning in action. IEEE Transactions on Systems, Man, and Cybernetics, 23(4), 981–992.

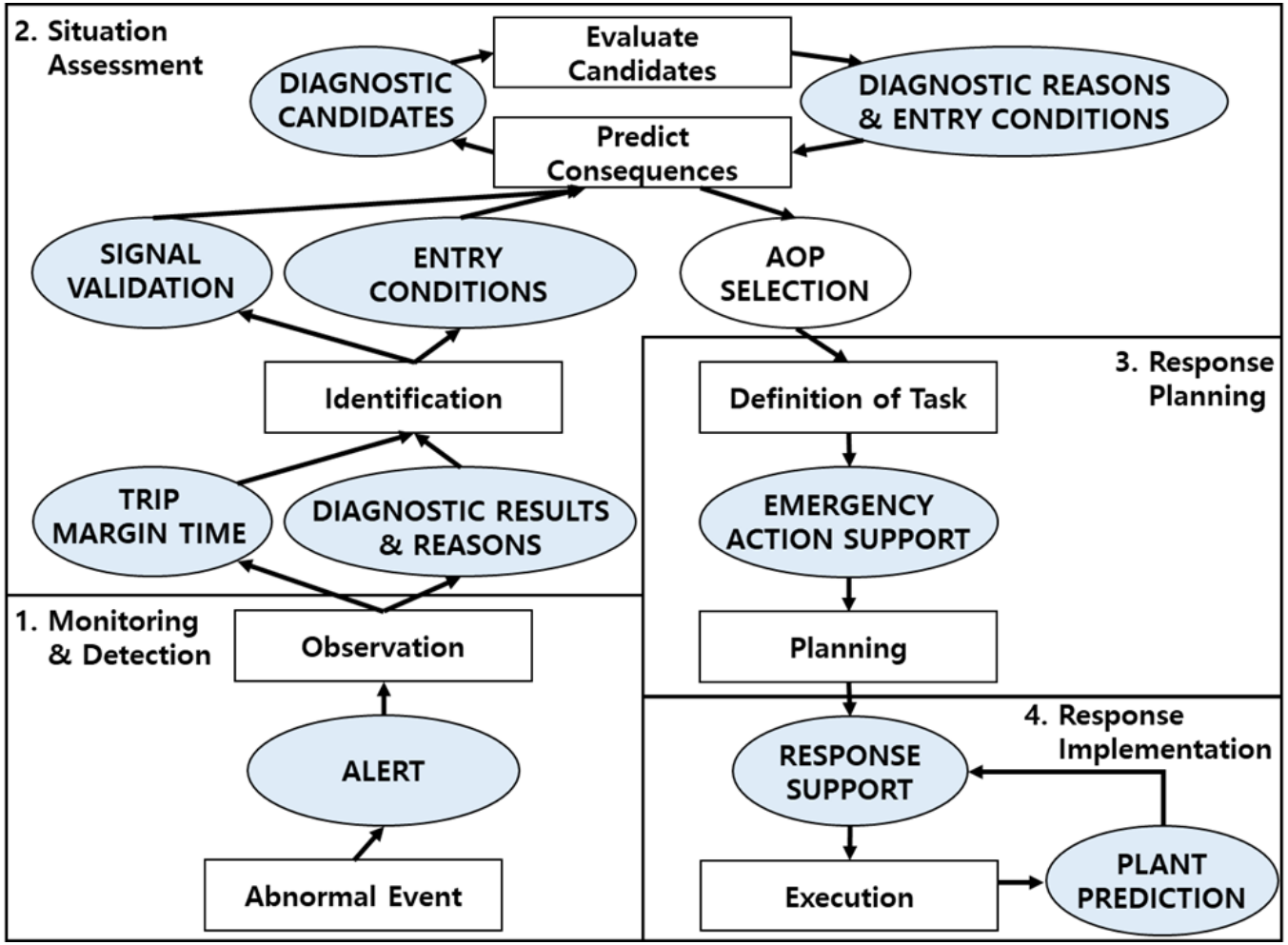
Adapted decision ladder for abnormal state diagnosis

- Adapted to NPP abnormal state diagnosis
- Diagnostic information mapped to cognitive states
  - State diagnosis module contains **monitoring/detection** and **situation assessment**

☐ Rectangles: Cognitive activity

○ Ovals: State of knowledge

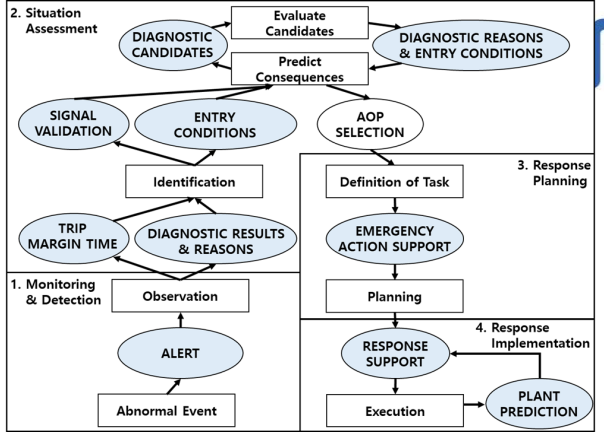
Decision ladder for abnormal operation management



02

Method

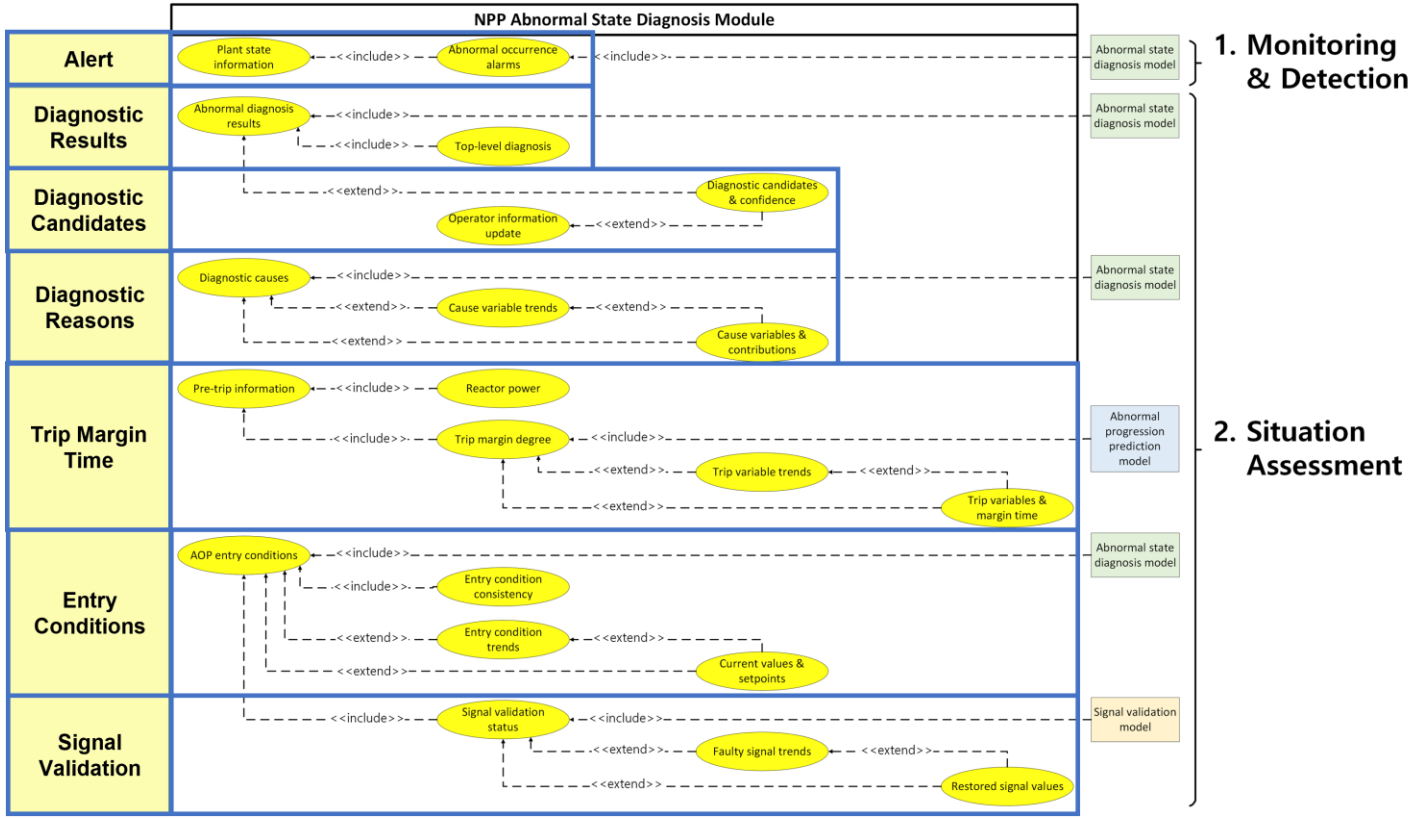
3-2. Information structure design: Use case diagram



Use case-based diagnostic information structure

- Structuring diagnostic information
- 1:1 mapping between state of knowledge and use case categories
- Relationship
  - Include: essential information
  - Extend: on-demand detailed information

Use case diagram for abnormal state diagnosis module



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Method

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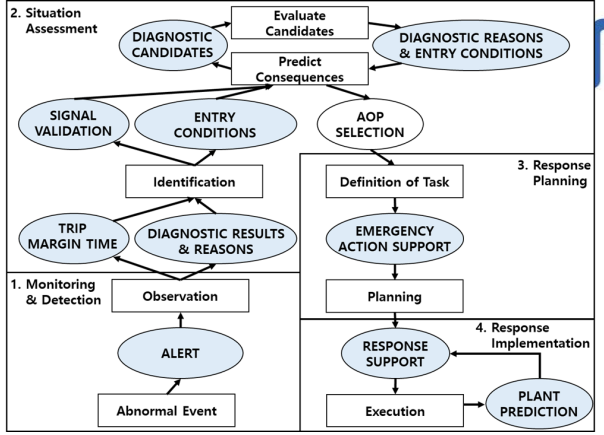
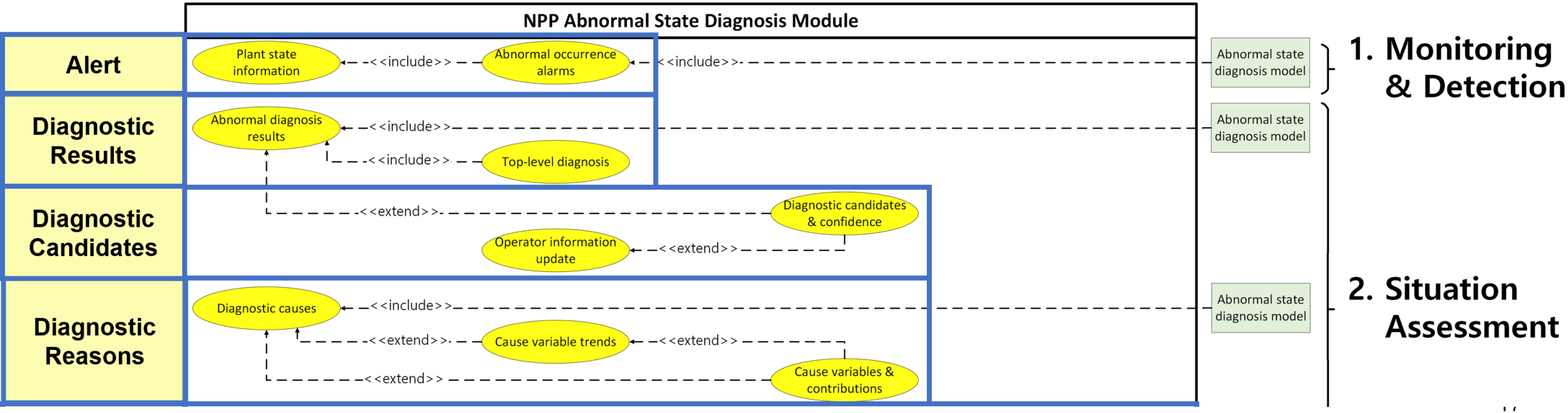


Use case-based diagnostic information structure

- Alert: Abnormal occurrence and plant state awareness
- Diagnostic results: Top-level diagnosis for current abnormal state
- Diagnostic candidates: Alternative abnormal states with confidence
- Diagnostic reasons: Related systems, causal variables, and their contributions

Use case diagram for abnormal state diagnosis module



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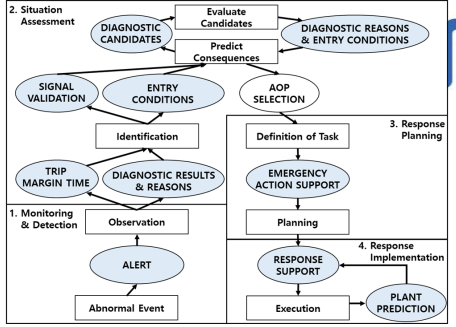

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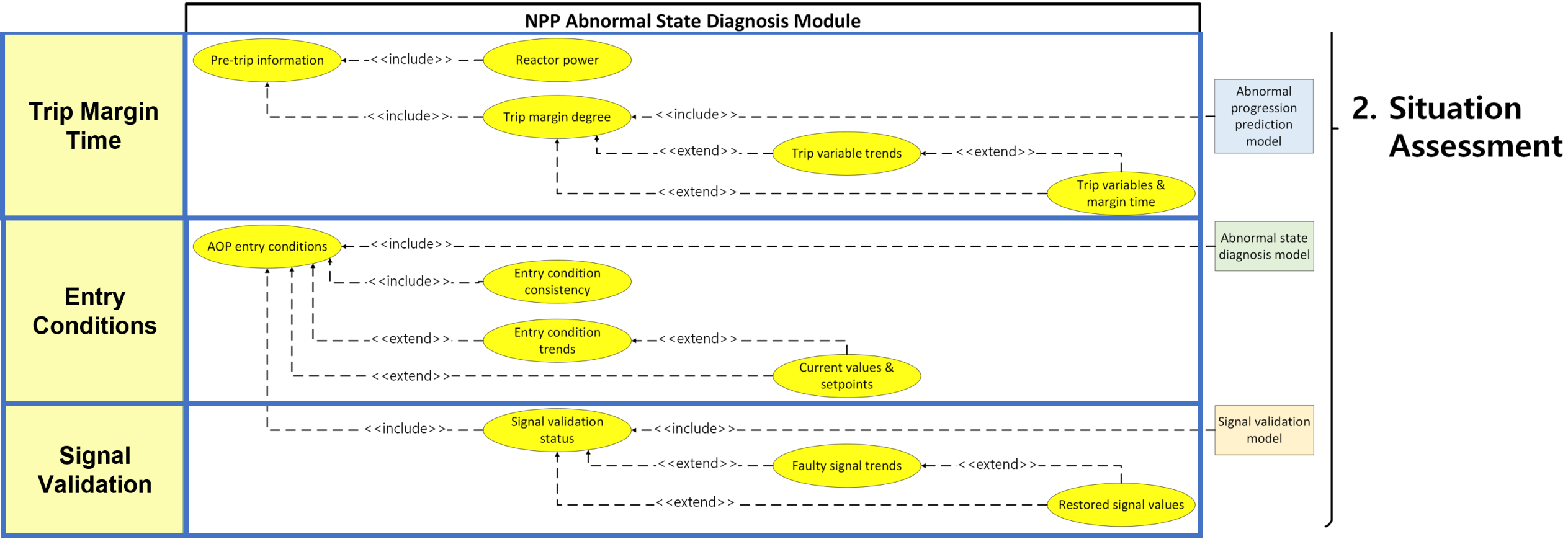
Use case-based diagnostic information structure

- Trip margin time: Available time before trip-related plant states
- Entry conditions: Consistency between diagnosis and abnormal operating procedure entry conditions
- Signal validation: Reliability of observed symptoms and sensor signals



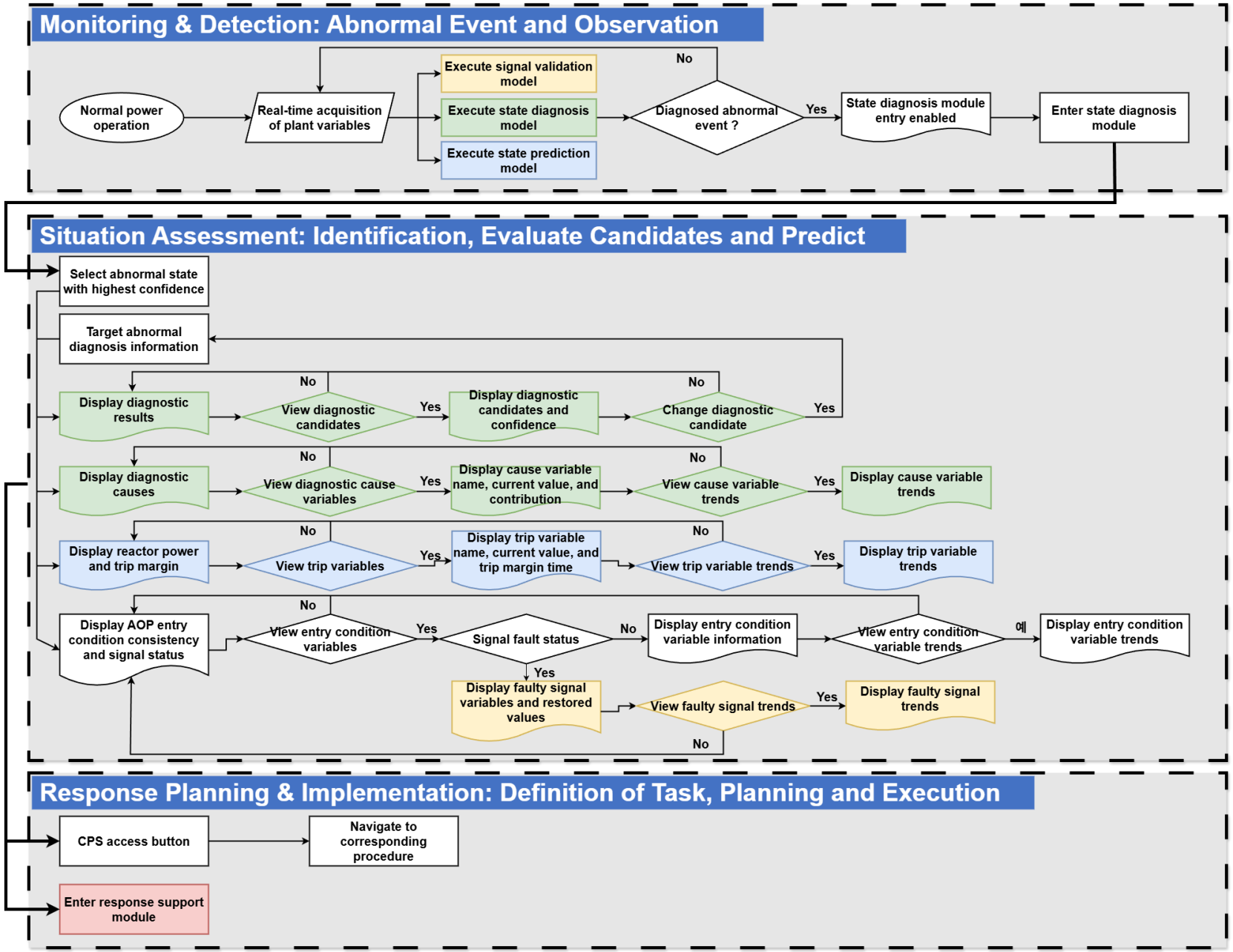
Method

3-3. Information structure design: Integrated flow

Integrated operator–state diagnosis interaction flow

- Operation flow based on the use case diagram
- Focusing on the "Monitoring & Detection" and "Situation Assessment"
- Interaction-based access to detailed supporting information

Integrated flow



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Integrated operator–state diagnosis interaction flow

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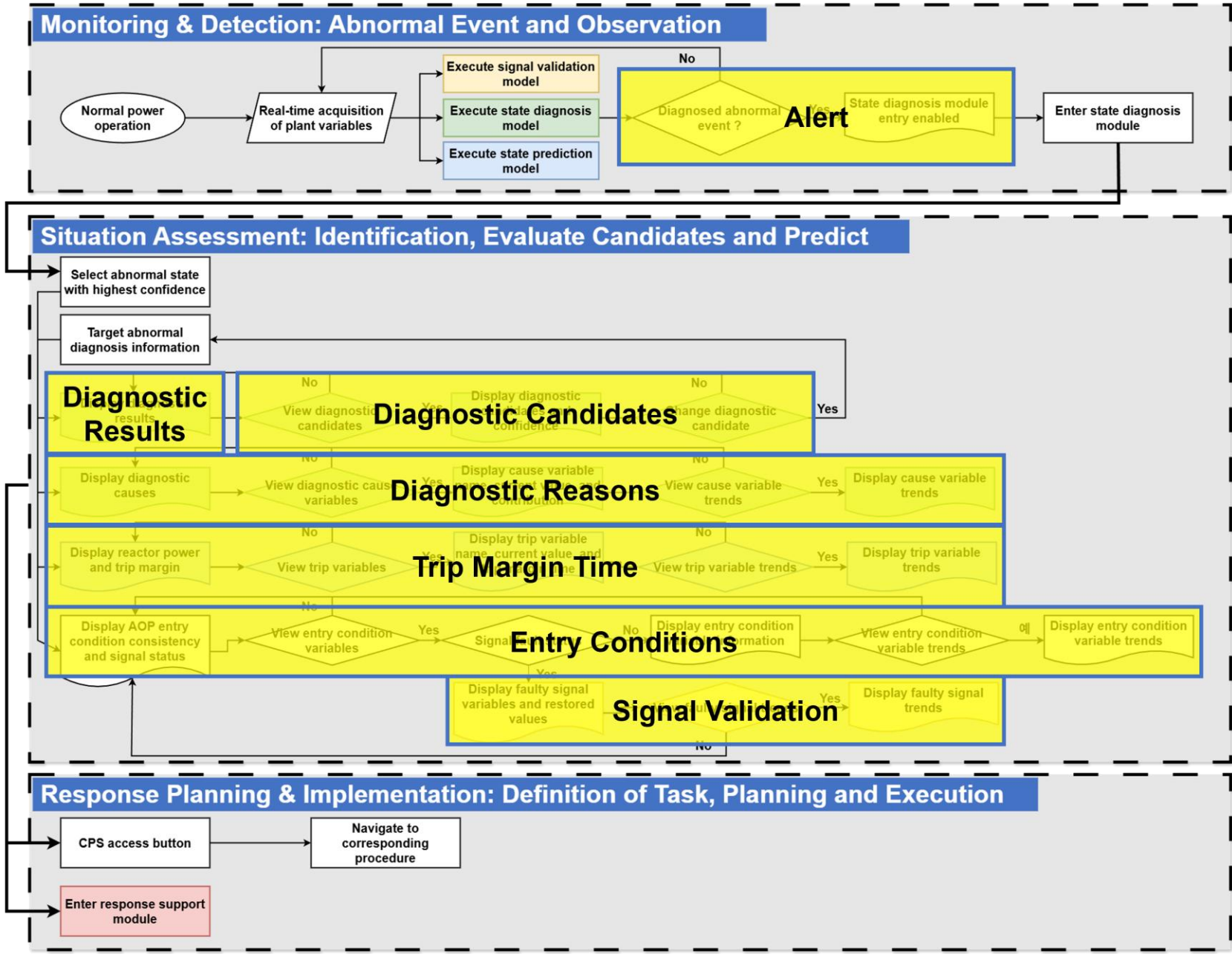
- **1:1 mapping between integrated flow and use case categories**

Integrated flow



03 Implementation

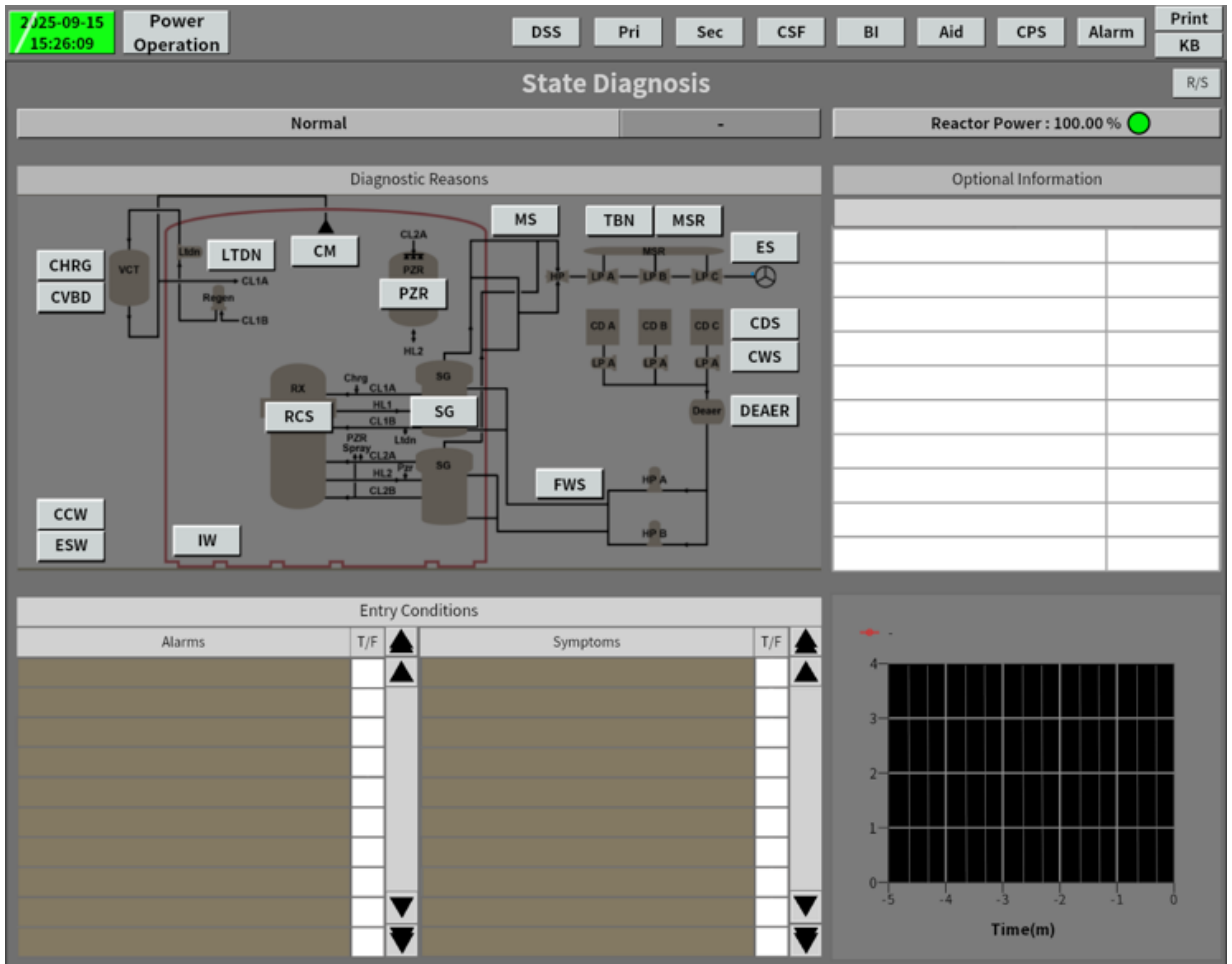
Implementation

1. State diagnosis module HSI configuration

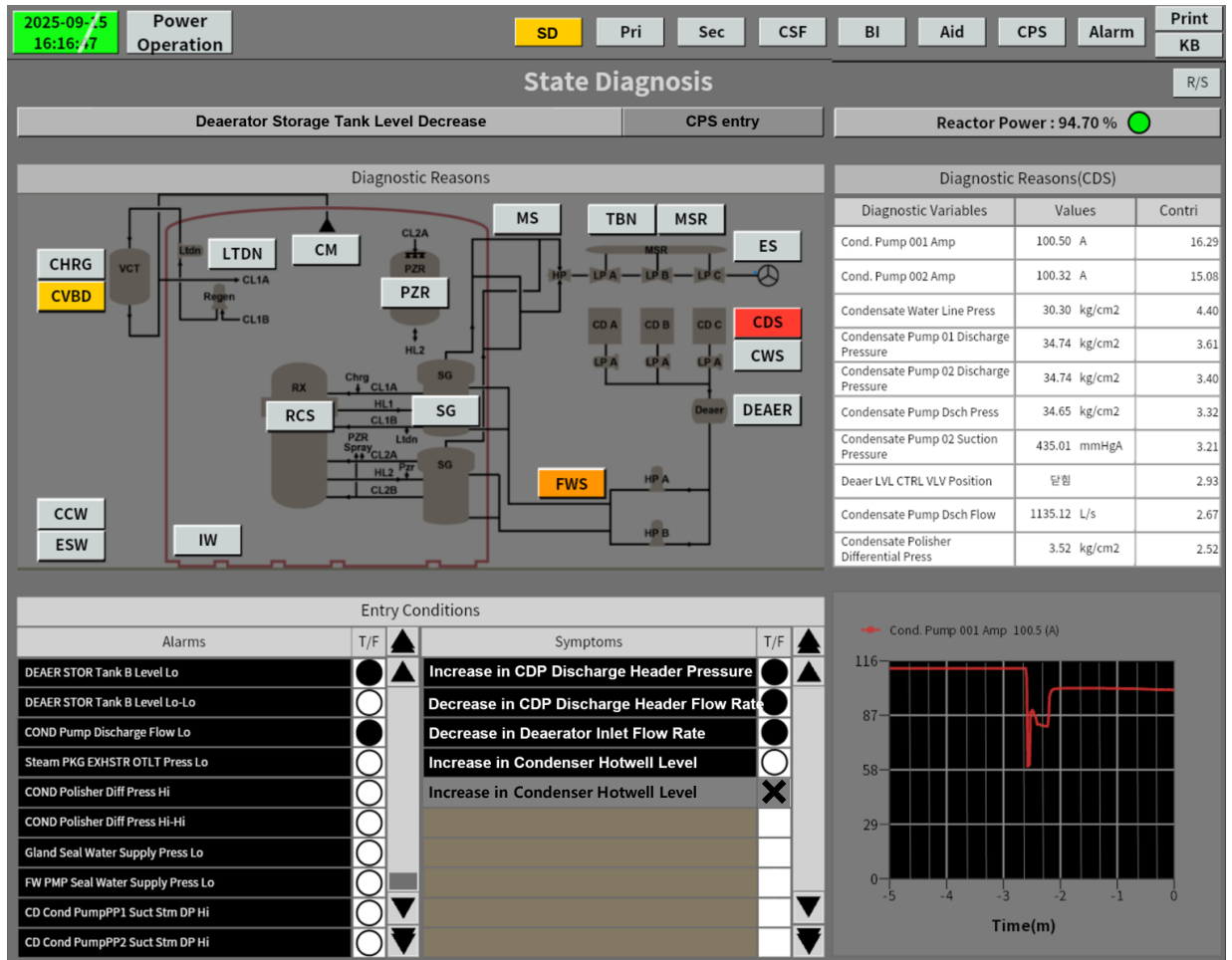
Configuration of the state diagnosis module Human-System Interface (HSI)

- State diagnosis module HSI built into the Information Processing System (IPS for operator decision support

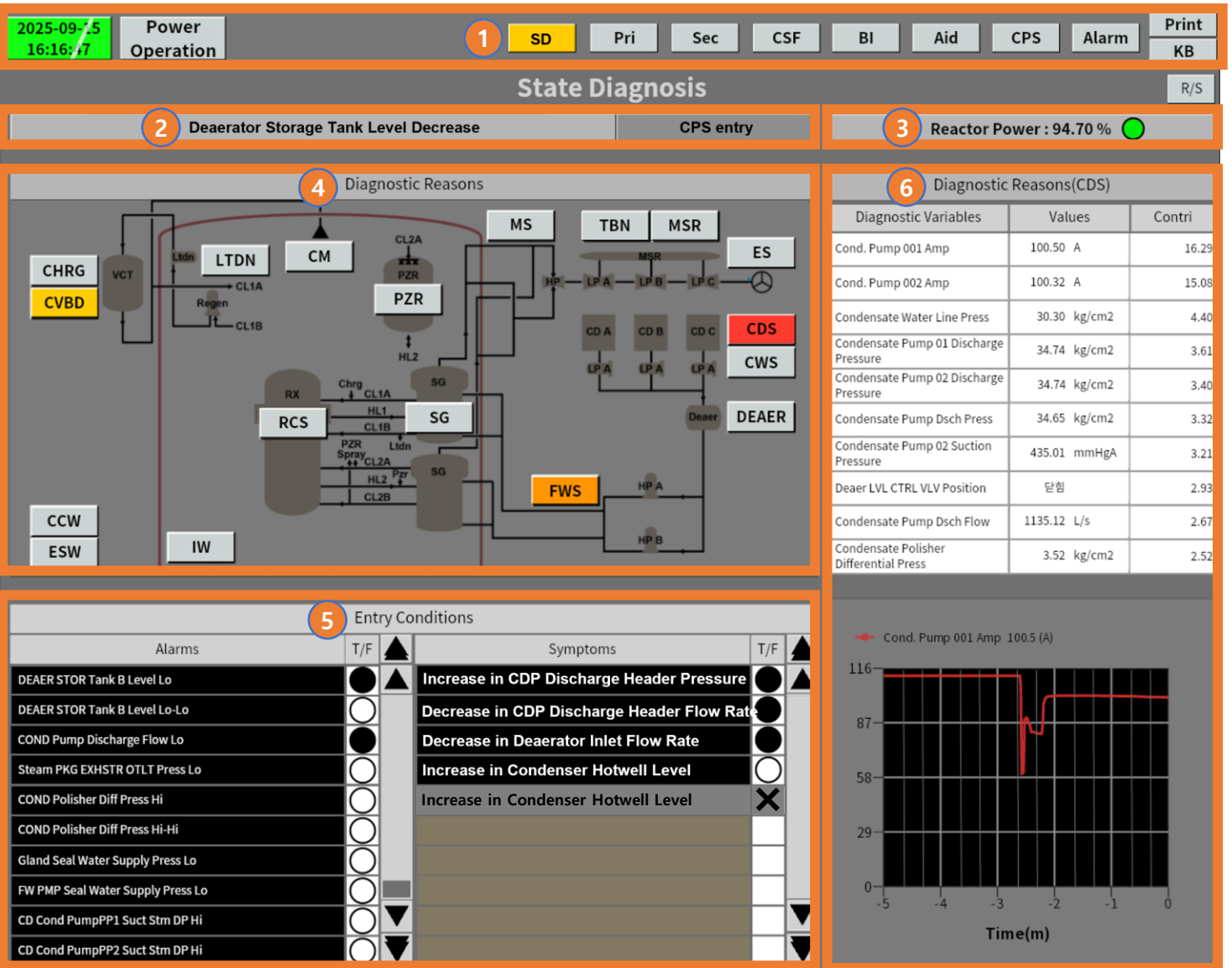
State diagnosis module HSI - normal



State diagnosis module HSI - abnormal



Configuration of the state diagnosis module Human-System Interface (HSI)

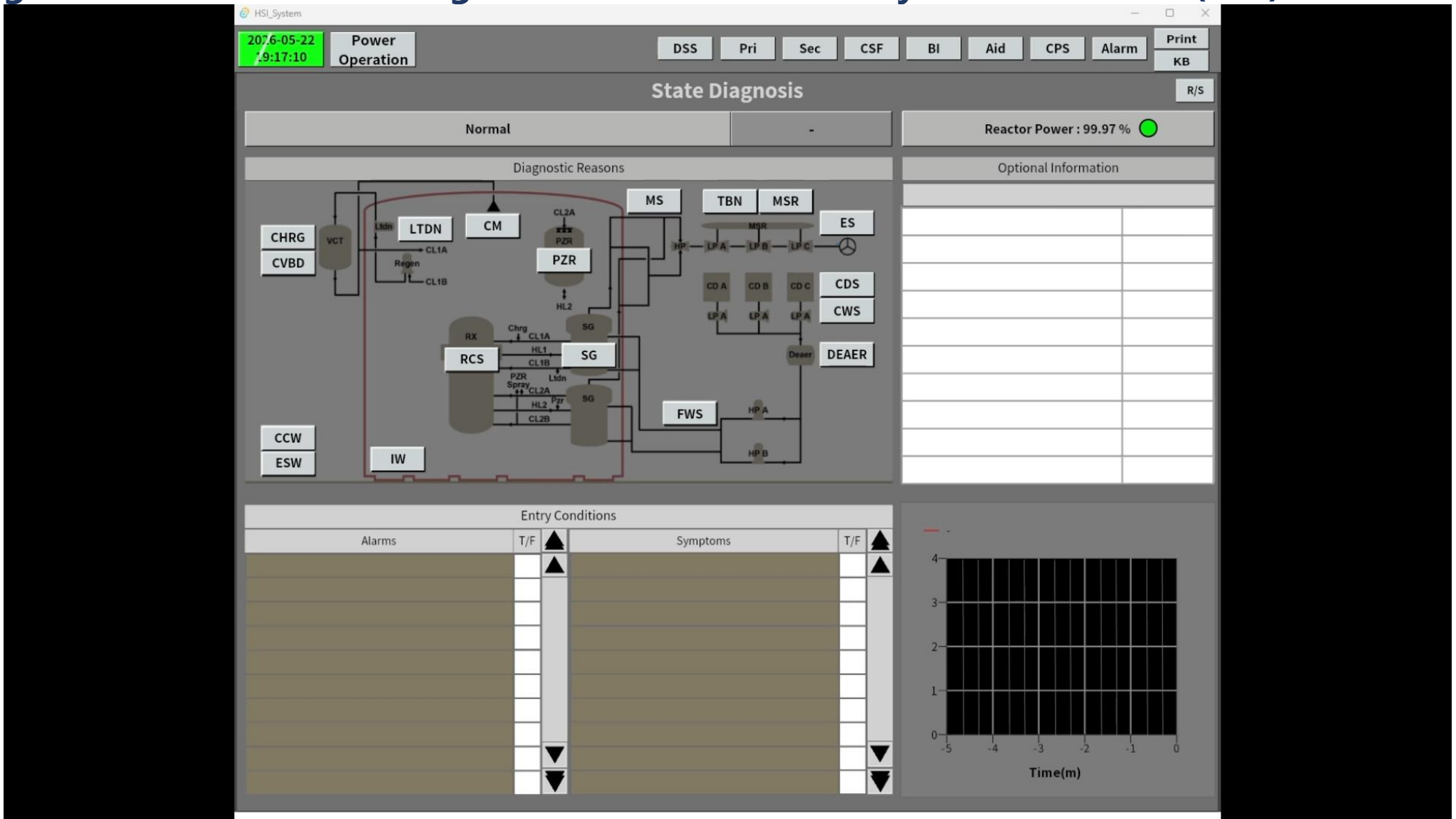


1. State diagnosis module navigation bar
   - Blinking "S/D" (State Diagnosis) indicator for AI-based abnormal state detection
2. State diagnosis result panel
   - Top-level diagnosis; candidates and confidence levels shown when clicked
3. Trip margin time panel
   - Color-coded urgency based on predicted time to trip
4. Diagnostic contribution panel
   - System-level color coding based on XAI contribution
5. Diagnosis verification panel
   - Consistency check with AOP entry conditions
6. Variable detail panel
   - Related variable values and trends for detailed inspection

Implementation

1. State diagnosis module HSI configuration

Configuration of the state diagnosis module Human-System Interface (HSI)



04 Conclusion

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- This study developed a cognitive-based state diagnosis module for operator decision support.
- Diagnostic information requirements were derived from the operator's cognitive process in abnormal situations.
- AI-derived information was organized according to the cognitive flow from situation recognition to diagnosis verification.
- The implemented HSI module supports operators in understanding the plant state, verifying the diagnosis, and making timely decisions.
- Future work will conduct operator-in-the-loop human factors evaluation to assess usability, situation awareness, and decision-making support.

Thank you