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Development of Operator Support System for the Abnormal Situations in NPPs

Younhee Choi[1], Ji Hun Park[1], Daeil Lee[2], Hyojin Kim[1], Sang Won Oh[1], Man Gyun Na[1], Jonghyun Kim[1, *]
[1]*Department of Nuclear Engineering, Chosun University, 309 Pilmun-daero, Dong-gu, Gwangju, 61452, Republic of Korea.*
[2]*Korea Atomic Energy Research Institute, 111, Daedeok-daero 989 Beon-gil, Yuseong-gu, Daejeon, 34057, Republic of Korea*
**Corresponding author*: jonghyun.kim@chosun.ac.kr

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1. Introduction.

Managing abnormal situations is one of the challenging tasks for operators in nuclear power plants (NPPs) [1], because 1) the operator should monitor many variables, diagnose the current situations, and implement appropriate mitigation measures, 2) many alarms may occur simultaneously, 3) a single alarm may occur in different abnormal conditions, and 4) there are many abnormal operating procedures, e.g., about one hundred of abnormal operating procedures (AOPs) in APR 1400.

Addressing the problems, many studies have suggested operator support systems to help operators in abnormal situations [2-6]. Some of them have shown their effectiveness in supporting operator decision-making. However, those systems focused on the support of diagnosis and decision-making tasks and did not support overall tasks in abnormal operations.

In this light, this study suggests an operator support system called AIDAA (Advisory, Intelligent Decision Aid for Abnormal operations) that can support the overall task in abnormal operations of NPPs. To do this, this study identified the design requirements using task analysis, strategy analysis, and the review of guidelines. Then, a conceptual design of AIDAA is suggested by satisfying the design requirements using appropriate AI techniques. Finally, this study implements a prototype of AIDAA using Python, PyQt5, and the compact nuclear simulator.

2. Development of AIDAA requirements

This study developed design requirements through three steps: 1) task analysis (TA) of abnormal operation, 2) diagnostic strategy analysis, 3) review of human factors engineering (HFE) guidelines.

2.1 Task analysis of abnormal operation

The objective of TA is to identify the operator tasks in abnormal operations and AIDAA's functions to support tasks. For the TA, this study reviews two documents: abnormal operating procedures (AOPs) and the information processing model for abnormal operations suggested by [1].

AOPs in Korean NPPs consist of five steps; the purpose of AOP, alarms and symptoms, automatically actuated systems, immediate response, and follow-up response, as shown the Fig. 1.

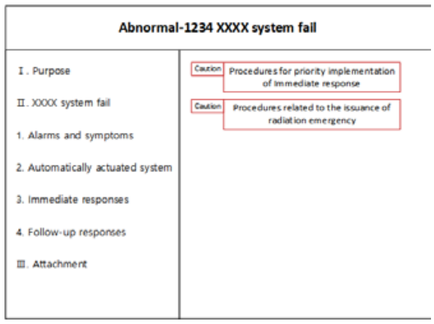


Fig. 1. Structure of AOPs

Kim and Kim [2] proposed an information processing model for the diagnosis tasks for abnormal situations. The proposed information processing model suggests cognitive tasks considering different abnormal situations, as shown in Fig. 2. The cognitive tasks are also summarized as follows;

- Perceiving alarms
- Identifying and performing urgent actions to prevent reactor trips
- Searching a cause of abnormal situations
- Selecting a relevant procedure
- Executing actions, the following procedure
- Executing actions to recover the plant status (if there is no relevant procedure)

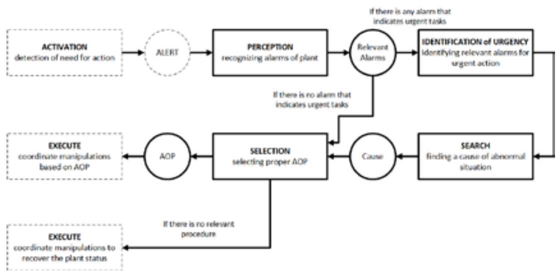


Fig. 2. Information processing model for diagnosis tasks [1]

Based on the review of these documents, this study identified the AIDAA requirements as shown in Table I.

Table I: AIDAA requirements resulting from TA

No.	Operators' tasks	AIDAA support	Source
1	Comparing plant status with the alarms and symptoms, automatic actuated systems provided by AOPs	Supporting the operators' comparison tasks	AOP
2	Performing execution of AOPs	Supporting operators' execution of AOPs	AOP
3	Perceiving alarms	Providing alarms and alarm response procedure	AOP, information processing model
4	Identifying and performing urgent actions to prevent reactor trips	Providing the need of urgent actions and predicting the reactor trips	information processing model
5	Searching a cause of abnormal situations	Providing the cause of abnormal situations and information to verify it such as alarms and symptom status, plant status	AOP, information processing model
6	Selecting relevant procedure	Providing relevant procedures	AOP, information processing model
7	Executing actions following procedure	Supporting operators' execution of actions following AOPs	AOP, information processing model
8	Executing actions to recover the plant status if there is no appropriate procedure	Providing the abnormal systems and situations with symptoms	information processing model

2.2 Review of the diagnostic strategies

To support operators' strategies of the diagnosis tasks in abnormal situations, the diagnostic strategies suggested by Rasmussen have been reviewed. Rasmussen proposed that operators apply two different strategies in the diagnosis tasks: symptomatic and topographic searches [7].

Symptomatic search is a strategy that identifies symptoms of a malfunction in a system and uses those symptoms to diagnose the cause of the problem [7]. This strategy is normally symptom-focused and rule-based or heuristic. It is used for quick problem identification, and enables the limited exploration of system structure.

Topographic search is a strategy that involves systematically narrowing for the location of a fault in a system. This strategy is system-focused, emphasis on system configuration, analytical and systematic. The result of this strategy includes the root cause identification.

Operators usually apply the symptomatic search when the appropriate procedure is available. Since an AOP provides alarms and symptoms that are expected in an abnormal event, operators compares the alarms and symptoms in the AOP with the actual status of NPP. If the plant status matches the pattern in the procedure, the AOP is accepted.

On the other hand, operators use the topographical search in case that there is no appropriate procedure for the current situation. If any procedure does not predefine the fault, they need to locate the faulty system, narrow down to the component level, and identify the failure of component. The good/bad mapping and a mental model for the normal status can be used as in the topographical search.

Based on this, some AIDAA design requirements for supporting operators' diagnostic strategies are derived as shown in Fig. 3.

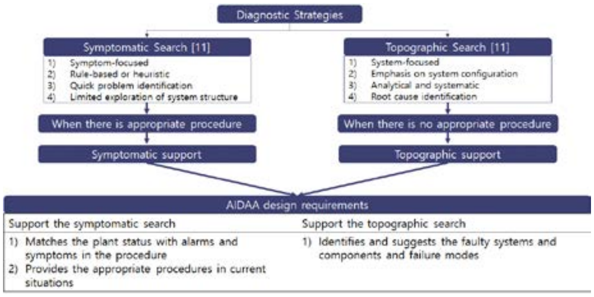


Fig. 3. AIDAA requirements in diagnostic strategies

2.3 Review of human factors engineering guidelines

To identify key functional and HSI-related requirements for AIDAA, this study reviews the HFE guidelines. Some HFE guidelines suggest functions and requirements appropriate for the design AIDAA, such [8-12]. As a result of the review of these guidelines, this study identifies the requirements of AIDAA as shown in Table II.

Table II: Summary of AIDAA's key functional and HSI-related requirements

No.	Key requirements	Source
1	Providing the alarms and alarm-related information, alarm response procedures	NUREG-0700 EPRI TR 3002004310
2	Providing the need of urgent actions	NUREG-0700 EPRI TR 3002004310
3	Providing the sorted alarms by occurrence time	NUREG/CR-6684
4	Providing the diagnosis support with the information for operators to quickly understand the current status	NUREG-0700 EPRI TR 3002004310
5	Providing the information about the current process being used and reasoning process	NUREG-0700 EPRI TR 3002004310
6	Monitoring the plant processes and other parameters, and present current, past, and possibly predicted future states of the plant and its system	EPRI TR 3002004310
7	Providing the material that the user must view in parallel to execute a procedure step	EPRI TR 3002004310 NUREG-0700 NUREG/CR-6634, EPRI TR 1015313
8	Presenting the warnings and cautions by using unique coding	EPRI TR 3002004310
9	Supporting the user control of procedure executions	EPRI TR 3002004310 NUREG/CR-6634
10	Providing the diagram related to occurred alarms of components.	NUREG-0700

2.4 Summary of AIDAA requirements

Based on the three-step of analyses, the fourteen key requirements of AIDAA were identified as showing in Table III.

Table III. Key requirements for AIDAA

No.	Key requirements	Source
1	Supporting the operators' comparison tasks	TA, Diagnosis strategy, HFE guidelines
2	Providing the cause of abnormal situations and information to verify it such as alarms and symptom status, plant status	TA, Diagnosis strategy, HFE guidelines
3	Providing alarms and alarm response procedure	TA, Diagnosis strategy, HFE guidelines
4	Presenting need of urgent actions Providing the need of urgent actions	TA, Diagnosis strategy, HFE guidelines
5	Predicting the reactor trips	TA, HFE guidelines
6	Providing relevant procedures	TA, Diagnosis strategy, HFE guidelines
7	Supporting operators' execution of actions following AOPs	TA, Diagnosis strategy
8	Suggesting recovery actions	TA, Diagnosis strategy
9	Identifying and suggesting the faulty systems and components and failure modes	Diagnosis strategy
10	Providing the information about the current process being used and reasoning process	HFE guidelines
11	Predicting the reactor trips	HFE guidelines
12	Providing the material that the user must view in parallel to execute a procedure step	HFE guidelines
13	Presenting the warnings and cautions by using unique coding	HFE guidelines
14	Providing the diagram related to occurred alarms of components.	Diagnosis strategy, HFE guidelines

3. Conceptual design of AIDAA

A conceptual design of AIDAA was suggested to satisfy the design requirements, as shown the Fig. 4. The AIDAA consists of four displays: 1) diagnosis support display, 2) procedure-based display, 3) function-based display, and 4) prediction display. This study also implemented them with appropriate AI techniques.

Fig. 4. Conceptual design of AIDAA

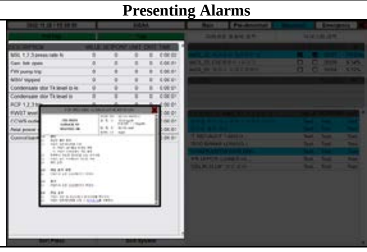
3.1 Diagnosis support display

The diagnosis support display consists of three sections: 1) alarm section, 2) procedure selection section, and 3) system selection section.

3.1.1 Alarm section

The alarm section provides the information of occurred alarms (e.g., occurrence time, current value, unit, set-point) and the link to alarm response procedures. The alarm section is implemented with the rule-based system that utilizes a predefined set-point. Table IV shows the display for the alarm section, the provided information, implementation techniques, and related design requirements.

Table IV. Diagnosis support; alarm section

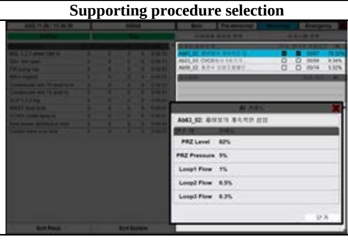
Function	Presenting Alarms
Display	
Information provided	– Providing occurred alarm information – Providing alarm response procedure
Method	– Rule-based system
Requirements	– 1, 3

3.1.2 Procedure selection section

The procedure selection section is designed to support the operator's selection of the appropriate AOP for the current situation. Table V shows the display for the procedure selection section, the information provided, implementation techniques, and related design requirements. This section suggests candidate procedures in the current abnormal situations (to support the symptomatic search) and also shows whether the procedure includes urgent actions. It provides the confidence levels of suggested procedure calculated by the AI algorithm and how many entry conditions for the procedure are satisfied. With this information, operators can select an appropriate procedure for the current situation. The candidate procedure is suggested by the gated recurrent unit-autoencoder (GRU-AE) and light gradient-boosting machine (LightGBM).

In addition, this section provides the reasoning process for the suggested candidate procedure using explainable AI called shapley additive explanations (SHAP). This is designed to satisfy the requirement #10. If operators click the right button on the procedure line, a pop-up display presents which parameter contributes how much to the procedure diagnosis. The details of the method are presented in [4].

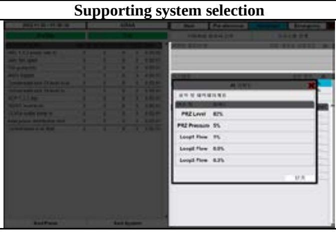
Table V. Diagnosis support; supporting procedure selection

Function	Supporting procedure selection
Display	
Information provided	– Suggesting the candidate procedure – Showing whether the procedure includes urgent actions or not – Providing a reasoning process for suggesting the candidate procedure
Method	– GRU-AE, LightGBM, SHAP
Requirements	– 1, 2, 4, 6, 10

3.1.3 System selection section

The system selection section is designed to support the operator's selection of the appropriate systems by providing abnormal systems if there is no appropriate procedure (to support the topographic search combined with the function-based display in Section 3.3). Similar to the procedure selection section in Section 3.1.2, this section suggests the candidate abnormal systems with the confidence level calculated by the AI algorithm (i.e., GRU-AE and LightGBM) as well as the number of alarms that occur in the system, as shown in Table VI. It also provides the reasoning process, which shows which parameter contributes to the decision of the abnormal system in percentage. This is implemented by the SHAP method. Please see [4] for the details of this section.

Table VI. Diagnosis support; supporting system selection

Function	Supporting system selection
Display	
Information provided	– Suggesting the candidate abnormal system – Providing a reasoning process for suggesting the candidate abnormal system
Method	– LightGBM, SHAP
Requirements	– 1, 2, 9, 10

3.2 Procedure-based display

The procedure-based display is to support the execution of the AOP selected in the diagnosis support display. It is a kind of computerized procedure systems for AOPs. As shown in Table VII, paper-based AOPs are transformed into computer-based forms. This display shows the purpose, alarms and symptoms, and automatic actions, immediate action. Through this, operators can conduct the AOP by checking each step.

Table VII. Procedure based support

Function	Supporting the execution of the AOPs
Display	
Information provided	– Suggesting the execution of computerized AOP selected in the diagnosis support display
Method	– Rule-based system
Requirements	– 4, 7, 12, 13

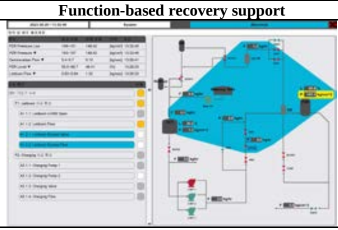
3.3 Function-based display

The function-based display helps operators to recover the functions of abnormal system without procedure. As shown in Table VIII, the display consists of three sections: alarm section, recovery action section and system diagram section. The alarm section provides the alarms that occur in the selected system.

The recovery action section suggests actions needed to recover the functions of abnormal system. This section suggests the action lists required to recover the functions. The actions required are highlighted in the yellow box. This section is implemented by the Soft Actor Critic (SAC) and Long Short-Term Memory (LSTM) [13].

The system diagram section displays the mimic of the selected system. The section is intended to support the topographical search strategy by highlighting the abnormal part of the system.

Table VIII. Function-based support

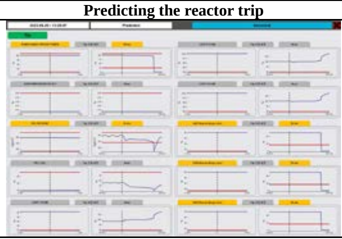
Function	Function-based recovery support
Display	
Information provided	– Providing the related alarms – Suggesting the recovery actions – Presenting the system diagram with highlighting abnormal system
Method	– SAC-LSTM
Requirements	– 8, 9, 10, 14

3.4 Prediction display

The prediction display provides the predicted trends of the reactor trip parameters. It provides the future trends of trip-related parameters in the long-term (2 hours) as well as short-term (2 minutes). It also calculates the remaining time to trip as shown in Table IX.

The prediction function has been implemented by combining Bidirectional-LSTM, Attention Mechanism (AM). The BiLSTM and AM enable to implement the long-term predictions of multiple variables with a single neural network. The details of the prediction method can be found in [14].

Table IX. Prediction of reactor trip

Function	Predicting the reactor trip
Display	
Information provided	– Predicting the future trends of trip parameters – Predicting the remaining trip time
Method	– Bi-LSTM, AM
Requirements	– 5, 10

4. Conclusion

In this study, an operator support system called AIDAA was proposed to support the overall tasks for abnormal operations. This paper identified the design requirements by conducting the TA about AOPs, the analysis of diagnostic strategies and the review of HFE design guidelines. Then, a design of AIDAA, which consists of four displays, was proposed. In addition, the implementation of the AIDAA was performed using appropriate AI techniques. The AIDAA is expected to reduce operators' workload and human error in abnormal situations by supporting the overall task of improving abnormal operations.

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