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An analytical approach to quantitative effect estimation of operation advisory system based on human cognitive process using the Bayesian belief network

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Abstract

The design of instrumentation and control (I&C) systems for nuclear power plants (NPPs) is rapidly moving towards fully digital I&C systems and is trending towards the introduction of modern computer techniques into the design of advanced main control rooms (MCRs) of NPPs. In the design of advanced MCRs, human–machine interfaces have improved and various types of decision support systems have been developed. It is important to design highly reliable decision support systems in order to adapt them in actual NPPs. In addition, to evaluate decision support systems in order to validate their efficiency is as important as to design highly reliable decision support systems. In this paper, an operation advisory system based on the human cognitive process is evaluated in order to estimate its effect. The Bayesian belief network model is used in the evaluation of the target system, and a model is constructed based on human reliability analysis event trees. In the evaluation results, a target system based on the operator's cognitive process showed better performance compared to independent decision support systems.

Keywords: Advanced main control room; Decision support system; Decision support system evaluation

1. Introduction

1.1. Background

The design of instrumentation and control (I&C) systems for nuclear power plants (NPPs) is rapidly moving towards fully digital I&C systems with an increased amount of automation, and the trend is towards the introduction of modern computer techniques into the design of advanced main control rooms (MCRs) of NPPs [1,2]. For advanced MCRs, computerized decision support systems continue to be developed and are intended to improve operator performance by filtering or integrating the raw process data, interpreting the plant state, prioritizing goals as well as by providing advice. They also help the operator focus their attention on the most relevant data and highest priority problems, and dynamically adapt response plans to changing situations. The computerized support of operational performance is needed in order to assist the operator, particularly in coping with plant anomalies so that the failures of complex dynamic processes can be managed as quickly as possible with minimum adverse consequences. Thus, various types of decision support systems have been developed, such as intelligent advisors, alarm systems, computer-based procedures, fault diagnostic systems, and computerized decision support systems. It is very important to design highly reliable decision support systems in order to adapt them in actual NPPs. In addition, to evaluate those support systems and validate their efficiency and reliability is as important as to design highly reliable decision support systems, because inappropriate decision support systems or automation systems can cause adverse effects [3]. There is abundant research regarding the evaluation of decision support systems for operators. These involve evaluations

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using various methodologies and factors. In experimental studies, operator performance with decision support systems such as information aid systems is estimated by the quality and accuracy of a diagnostic performance [4] as well as by other various subjective or objective measurements. For a modernized interface consisting of LCDs and CRTs, the number of navigated windows and time spent for diagnosis are used as the criteria for evaluating operator performance [5]. In theoretical research, various types of models have been posited, such as the discrete function model [6] and the Bayesian belief network (BBN) [7].

1.2. Objectives

The target system of this work is an operation advisory system that aids the cognitive process of operators of advanced NPPs [8]. The operation advisory system is a type of integrated decision support system for advanced MCRs based on the human cognitive process. As MCRs have evolved, additional decision support systems have been adapted. Therefore, combinations and cooperation in decision support systems are important in advanced MCRs, and a design basis to select appropriate decision support systems and to integrate the decision support systems is necessary. The operation advisory system to aid the cognitive process of an operator proposes decision support systems that support each activity in the human cognitive process.

In this work, the BBN is used as the basic method that estimates the effect of the target system. In order to construct the BBN model, the human reliability analysis (HRA) event tree is used. Moreover, several performance shaping factors are considered for evaluations and the human error probabilities (HEPs) described in NUREG/CR-1278 [9] are used.

2. Operation advisory system to support cognitive activities of a operators underlying ATHEANA

2.1. Cognitive process model for NPP operators

The operation advisory system to aid the cognitive process of operators is developed based on the major cognitive activities for NPP operations underlying ATHEANA (A Technique for Human Error Analysis) [10,11]. The major cognitive activities for NPP operations underlying ATHEANA are (1) monitoring and detection, (2) situation assessment, (3) response planning, and (4) response implementation [11].

Operators in an MCR monitor and control a NPP according to the human cognitive process. Fig. 1 shows the relationship between a human, an HMI, the I&C systems, and a plant [8]. All HMIs in MCRs have display systems and implementation systems for monitoring and controlling the plant. Operators obtain information concerning a plant through the display systems and control the plant through the use of implementation systems. Human operators obtain plant information through a display system in the HMI layer and assess the current situation using the obtained information. In the next step, the human operators select the operations corresponding to the assessed situation. Finally, they implement the operations. The operators' operation processes can be represented in this way using the human cognitive process.

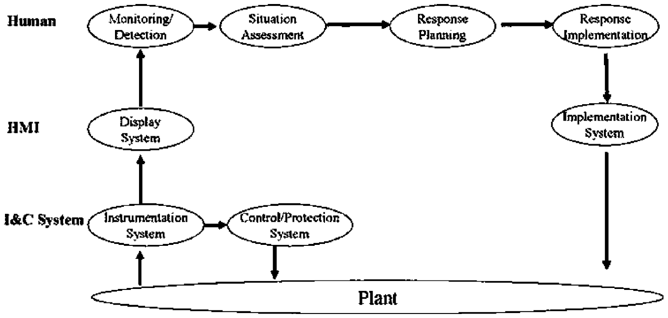

Fig. 1. NPP operator's operation process.

2.2. Components of the operation advisory system

The operation advisory system is not a system that helps with a task or supports one or two cognitive activities. It supports every major cognitive activity by integrating the decision support systems that support individual cognitive activities. It aids the operator's entire operation process; monitoring plant parameters, diagnosing the current situation, selecting corresponding actions for the identified situation, and performing the actions. Therefore, it is important to suggest appropriate decision support systems that support the cognitive activities efficiently. For example, several decision support systems that are under development or have been developed are suggested as appropriate decision support systems, as shown in Fig. 2. They consist of main systems and subsystems. Four main systems are proposed to support the four cognitive process activities: a display system, a fault diagnosis system, a computerized procedure system, and an operation validation system. Moreover, using the main systems together, several subsystems are suggested. All of the systems support the major cognitive activities. As the proposed system can perform an operation process identical to that of an operator in its support of the cognitive process of an operators it is possible to detect human errors during operation processes. Thus, the system functions as an advisory system for the prevention of human errors.

For evaluations in this work, only four main decision support systems are considered, as shown in Fig. 3. The first main system is a display system that supports monitoring and detection activity. The display system provides an efficient display and interface design, and it involves an improvement with its integrated graphic displays, configurable displays [12], and its ecological interface design [13]. The display system also improves operator perception and awareness: operators can perceive the plant status more quickly and easily using the

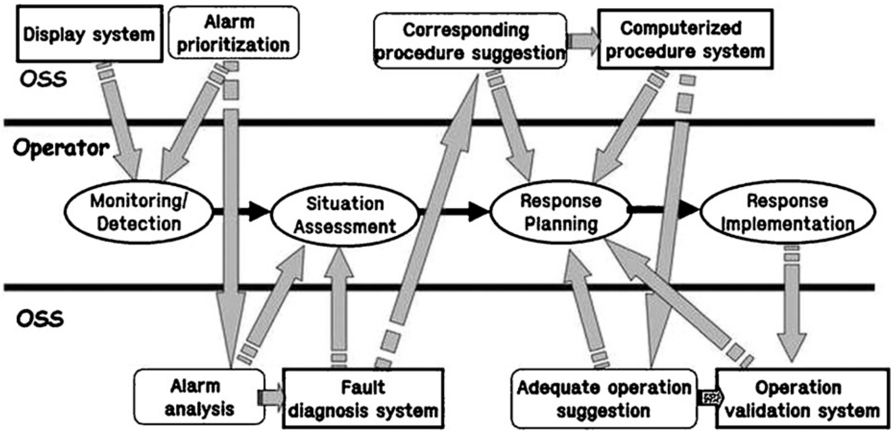

Fig. 2. Decision support systems based on a human cognitive process model.

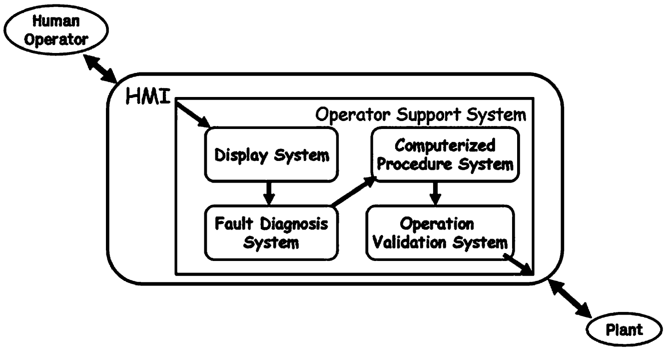

Fig. 3. The architecture of the target system.

information from the improved display system. In the evaluations, only digital indicators are considered as one part of the advanced display system. Secondly, a fault diagnosis system is suggested to support the situation assessment activity. The fault diagnosis system detects faults and informs the operator of a list of possible faults and their expected causes; therefore, it makes situation assessment easier by quickly supplying the diagnosis results. Several fault diagnosis systems have been developed using knowledge bases [14], neural networks [15,16], genetic algorithms [17], and other resources. The third main system is a computerized procedure system that supports the response planning activity. Operators in NPPs generate plans to operate and maintain NPPs according to written operating procedures. Thus, a computerized procedure system can be helpful for response planning activity. In a computerized procedure system, information concerning procedures and steps, relationships between the procedures and steps, and the plant parameters needed to operate the plant are displayed [18,19]. Lastly, for the response implementation activity, the operation validation system validates the actions performed by the operators. If the actions that are taken by operators are in the operation candidate list and are deemed appropriate, the actions will then be performed without interruption. However, if the actions are deemed inadequate for the current situation, the operation validation system interrupts the actions and warns the operator. This system gives operators a chance to double-check and confirm their actions. There have been several research papers that consider operation validation systems [20].

3. Quantitative effect estimation of the target system

Several kinds of decision support systems were introduced in the previous section. They can be used as an independent system or as an integrated system to support entire cognitive activities. In this section, the effects are estimated in cases where no decision support system is used, one or two decision support systems are used, and all four decision support systems that aid complete cognitive activities are used. Evaluations are performed using the BBN model, developed by Kim and Seong, for situation assessment of a human operator [7,21]. Based on the BBN model for situation assessment, several nodes are added in order to consider decision support systems. The human operator's situation assessment is represented by the Bayesian inference method in Kim and Seong's BBN model. HRA event trees are used to define additional nodes and their relations pertaining to decision support systems. Several performance shaping factors are considered in order to create a model that considers human operators. Operator expertise and operator stress level are used as performance shaping factors. To perform the evaluations, several assumptions are made as we do not have clearly defined values about the reliability and the estimated effects of the decision support systems. Evaluations are performed for two scenarios based on the implemented BBN model under certain assumptions.

3.1. BBN model for situation assessment of a human operator

The BBN model used for situation assessment of a human operator is taken from the research of Kim and Seong [7]. The mathematical model for the I&C systems and human operators where the interdependency between I&C systems and human operators is considered is similar to that used by Kim and Seong [7]. Fig. 4 briefly summarizes the structure of the model and definitions of the variables. X indicates the plant state, Z_i's ($i = 1, 2, \ldots, m$) indicate various sensors and Y_i's indicate various indicators. The variables are defined in mathematical form as follows:

$$X = \{x_1, x_2, \ldots, x_l\}, \tag{1}$$

$$Y_i = \{y_{i1}, y_{i2}, \ldots, y_{in_i}\} \quad \text{where } i = 1, 2, \ldots, m, \tag{2}$$

$$Z_i = \{z_{i1}, z_{i2}, \ldots, z_{in_i}\} \quad \text{where } i = 1, 2, \ldots, m. \tag{3}$$

It is assumed that operators have deterministic rules on the dynamics of the plant. The deterministic rules on the dynamics of the plant can be described using conditional probabilities, as follows:

$$P(y_{ij}|x_k) = \begin{cases} 1 & \text{if } y_{ij} \text{ is expected upon } x_k, \\ 0 & \text{if } y_{ij} \text{ is not expected upon } x_k. \end{cases} \tag{4}$$

It is assumed that NPP operators use the Bayesian inference to process incoming information, so that the situation assessment of human operators is quantitatively described using the Bayesian inference. The details of the explanation are described by Kim and Seong [7,21]. Mathematically, if the operators observe y_{ij} on the indicator Y_i, the probability of a state of the plant x_k can be revised as follows:

$$P(x_k|y_{ij}) = \frac{P(y_{ij}|x_k)P(x_k)}{\sum_{k=1}^{l} P(y_{ij}|x_k)P(x_k)}. \tag{5}$$

3.2. HRA event trees

The BBN model developed by Kim and Seong [7] is modified by adding nodes related to decision support systems. To define the relations among those nodes in the modified BBN model, HRA event trees are used. Fig. 5 shows the basic HRA event tree, which does not include any decision support system. The final operation result is correct only if all tasks over the four steps are correct. a_c and a_w indicate the probabilities that a human operator reads an analogue indicator correctly or incorrectly. b_c and b_w indicate the probabilities of correct and incorrect situation assessment by a human operator; c_c and c_w indicate the probabilities of right or wrong operation selection by a human operator without checkoff provisions; and d_c and d_w indicate the probabilities as to whether a human operator performs an action correctly.

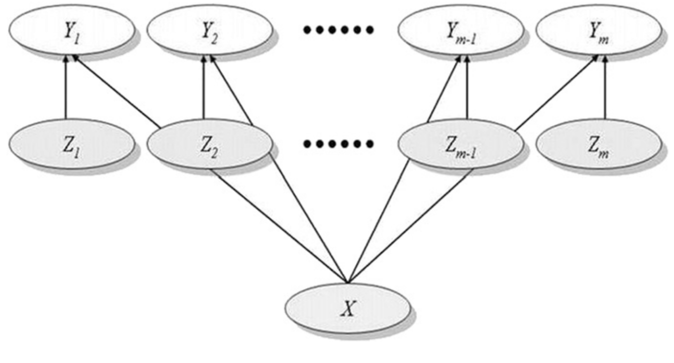

Fig. 4. Model for operators' rules on the dynamics of the plant.

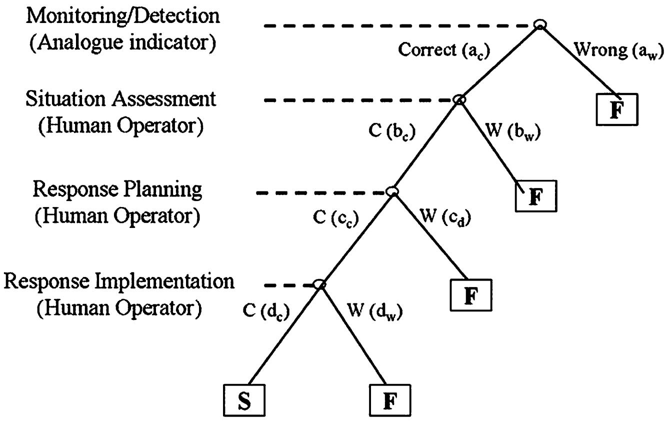

Fig. 5. HEP event tree in the case of no decision support system.

If digital indicators are used instead of analogue indicators, the HEP in reading digital indicators should be used instead of that for analogue indicators. In this case, the structure of the basic HRA event tree is not changed. e_w indicates the HEP in reading digital indicators. Also, if a function for checkoff provision is provided by the computerized procedure system, the HEP for omission error should be changed to an HEP that considers checkoff provision. In this case, the structure of the basic HRA event tree is not changed. g_w indicates the HEP for omission error when a function for checkoff provision is provided.

However, when a fault diagnosis system or an operation validation system is used, new branches are added to the basic HRA event tree, as those systems detect erroneous decision making and provide an additional opportunity to correct such errors. Fig. 6 shows the HEP event tree for those cases. f_c and f_w indicate the probabilities whether the fault diagnosis system generates correct results, and h_c and h_w indicate the probabilities whether the operation validation system detects operator's wrong actions. Additionally, three parameters are considered with regard to recovery probabilities. These parameters represent the cases where the decision of the human operator is different from that of the decision support systems. The whole HRA event tree that considers these parameters is shown in Fig. 6. The recovery probability q means that the human operator does not changes his/her correct decision even if the fault diagnosis system generates wrong results. Because the fault diagnosis system provides a list of possible faults and their expected causes, operators are capable of identifying inappropriate recommendations from the fault diagnosis system based on their knowledge and experience. q represents the probability that the human operator recognizes wrong diagnosis results from the fault diagnosis system. r indicates the recovery probability that the human

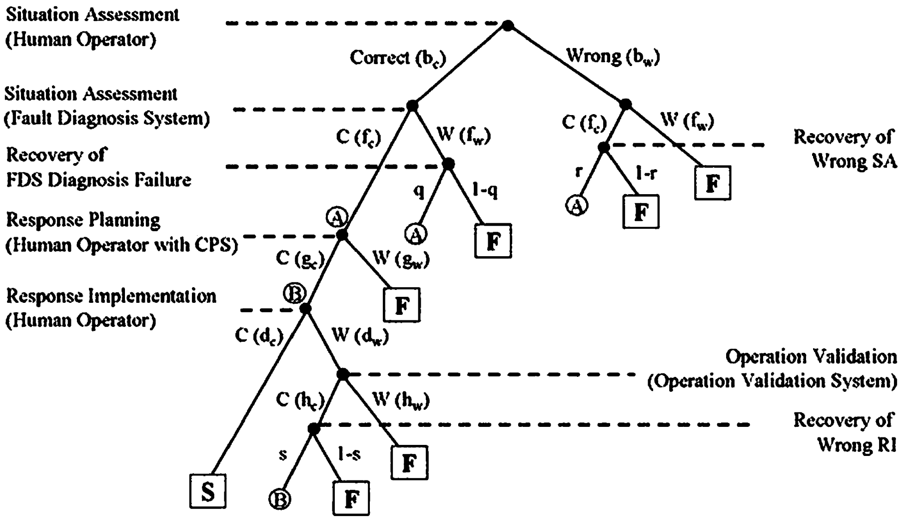

Fig. 6. HEP event tree when all decision support systems are used.

operator changes his/her decision according to correct results of the fault diagnosis system when he/she assesses the current situation incorrectly. When operators assess the current situation incorrectly, they can identify their faults by consulting the correct diagnosis results of the fault diagnosis system. r represents the probability of those cases.

When the fault diagnosis system is considered, the probability of a correct situation assessment is defined as follows in mathematical form:

$$\text{probability of correct situation assessment} = b_c(f_c + f_w q) + b_w f_c r, \tag{6}$$

q: recovery probability of diagnosis failure of the fault diagnosis system by the human operator;
r: recovery probability of wrong human operator situation assessment by the fault diagnosis system.

The objective of the operation validation system is to detect an operator's commission error, which is an inappropriate action for the current situation. s indicates the case where the operator recognizes his/her mistake via a operation validation system warning. When the operation validation system is used, the probability of correct response implementation is defined as follows in mathematical form:

$$\text{probability of correct response implementation:} \quad d_c + d_w g_c s, \tag{7}$$

s: recovery probability of wrong human operator response implementation by the operation validation system.

Based on the implemented HRA event trees, the modified BBN model is constructed by adding nodes for the decision support systems, as shown in Fig. 7.

3.3. Assumptions for evaluations

The assumptions made for the evaluations are described in this section. Several assumptions are from the model developed by Kim and Seong [21]. Decision support systems such as the fault diagnosis system and operation validation system are still in development, and as such there are no HEP values for these entities. The objective of this work is not to analyze the impact of certain specific systems that have already been developed but to estimate the effect of the integrated decision support system supporting cognitive activities. Therefore, values of several parameters pertaining to decision support systems are assumed in this work.

The software tool used here is Hugin which is one of software tools for the analysis of Bayesian networks [22,23]. The evaluation model shown in Fig. 8 is developed based on the following conditions and assumptions:

1. For simplicity, only four representative states of the plant, normal operation, loss of coolant accident (LOCA), steam generator tube rupture (SGTR), and steam line break (SLB), are considered in the evaluations. Therefore,

   $$X = \{\text{normal operation, LOCA, SGTR, SLB}\}.$$

2. For simplicity, only 15 sensors and indicators, reactor power, generator output, pressurizer pressure, pressurizer level, steam/feedwater deviation, containment radiation, secondary radiation, wide water level of steam generator (SG) A and B, pressure of SG A and B, feedwater flowrate of SG A and B, and steam flowrate of SG A and B are considered in the evaluations. It is also assumed that the NPP operator knows that each indicator has three different states: increase, no change, and decrease.

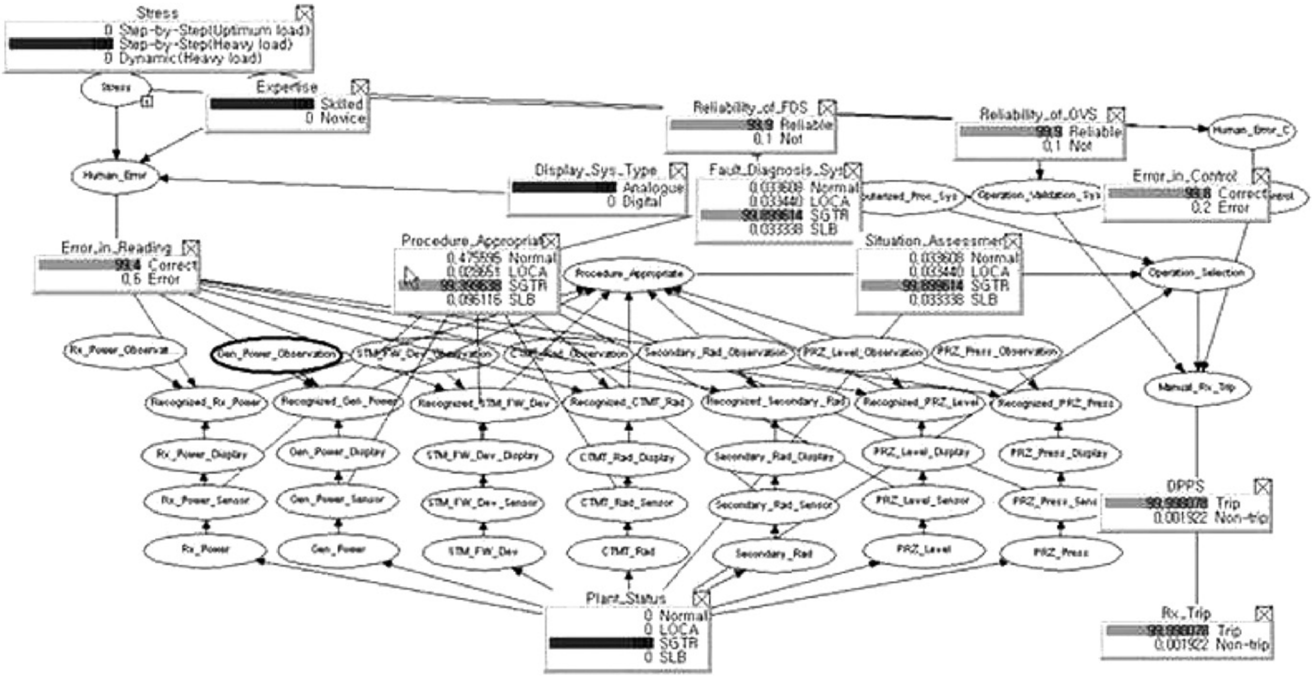

Fig. 7. BBN model for the evaluation.

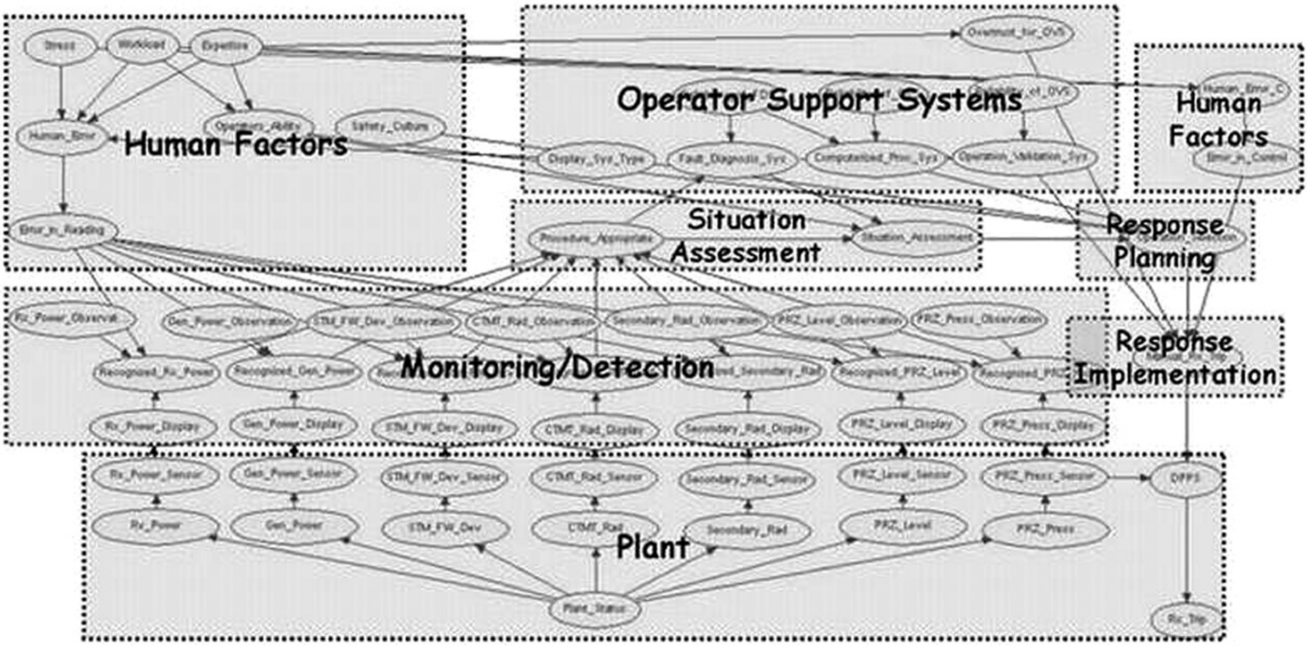

Fig. 8. BBN model for Case 7.

Therefore,

$$Y_i = \{\text{increase, no change, decrease}\} \quad \text{where } i = 1, 2, \ldots, 15.$$

3. The possibilities of sensor failures are considered. For simplicity, the NPP operator is assumed to believe that all 15 sensors have an equal unavailability, 0.001, and that each sensor has three failure modes: fail-high, stuck-at-steady-state, and fail-low. Therefore, Z_i's are given as follows:

$$Z_i = \{\text{normal operation, fail-high, stuck-at-steady-state, fail-low}\} \quad \text{where } i = 1, 2, \ldots, 15.$$

4. It is assumed that the NPP operator believes that the probability distribution for Z_i's, i.e. $p(Z_i)$s, are given

Table 1
HEP for reading

Task load	Step-by-step (optimum load)		Step-by-step (heavy load)		Dynamic (heavy load)	
Expertise	Skilled	Novice	Skilled	Novice	Skilled	Novice
Analogue indicator	0.003	0.003	0.006	0.012	0.015	0.030
Digital indicator	0.001	0.001	0.002	0.004	0.005	0.010

Table 2
HEP of omission per item of instruction when use of written procedures is specified

		Median joint HEP	EF
Without checkoff provisions	Short list (⩽10 items)	0.003	3
	Long list (>10 items)	0.01	3
With checkoff provisions	Short list (⩽10 items)	0.001	3
	Long list (>10 items)	0.003	3

Table 3
HEP of commission in operating manual controls

Select wrong control on a panel from an array of similar-appearing controls	Median joint HEP	EF
Identified by labels only	0.002	3
Arranged in well-delineated functional groups	0.001	3
Which are part of a well-defined mimic layout	0.0005	10

as follows:

$$p(Z_i) = \{0.999, 0.0001, 0.0008, 0.0001\}.$$

5. Without any observation, the initial probability distribution for the plant state is assumed to be as follows:

   $$P(x) = \{0.9997, 0.0001, 0.0001, 0.0001\}.$$

   We select the four plant states and the 15 indicators simply because the combination of the four states and the 15 indicators is useful for demonstration of the model. It is also assumed that operators consider all of the 15 indicators in order to assess the current situation.
6. Two performance shaping factors are considered, operator expertise and operator stress level. Since the HEPs used in the evaluations are from NUREG/CR-1278, the performance shaping factors mainly used in NUREG/CR-1278 are used. The expertise has two states, a novice group and a skilled group. The stress level changes according to the task load, and the task load factor is assumed to have three states, a step-by-step task with an optimum load, a step-by-step task with a heavy load, and a dynamic task with a heavy load.
7. Indicators are classified into two types: analogue and digital indicators. The HEPs for reading indicators in NUREG/CR-1278 are used and are shown in Table 1. Three factors are considered for the HEPs in the reading: task load, expertise, and type of indicator.
8. It is assumed that operators without the computerized procedure system do not use checkoff provisions, and that the computerized procedure system provides a function for checkoff provisions. Table 2 shows the values used as the HEPs of omission error. The length of the target list and the usage of a checkoff provision are considered for the HEPs for the omission of an item. It is assumed that the target operating procedure has more than 10 steps, as almost all emergency operating procedures have more than 10 steps.
9. The possibilities of action error, e.g. pushing a wrong button, in the manual control are considered. There may be no commission error or negligible error if there is just one control switch, such as a reactor trip switch. However, it is assumed that an operator can commit a commission error if there are similar control switches, such as an SG A isolation switch or an SG B isolation switch. HEPs for such commission error may depend on interfaces, and NUREG/CR-1278 provides HEPs considering these factors, as shown in Table 3. It is assumed that the SG isolation switches are identified by labels only.
10. Because we do not have estimated values about the reliability and the effect of the fault diagnosis system and operation validation system, three reliability levels are assumed for these systems: 95%, 99%, and 99.9%.
11. In the evaluation model, group operations are not considered. In fact, in real MCRs, there are more than three operators. For simplicity, however, operation processes of one operator are considered.
12. It is assumed that a human operator is able to detect wrong results of the fault diagnosis system and to correct his/her wrong decisions by providing appropriate advice of the decision support systems. It is also assumed that skilled operators have more

capabilities against those cases than novice operators. For the recovery probability '*q*', it is assumed that a skilled operator can detect a wrong result of the fault diagnosis system at a rate of 50% and a novice operator can detect that at a rate of 30%. For the recovery probability '*r*', it is assumed that a skilled operator can correct his/her wrong decision according to the correct diagnosis of the fault diagnosis system at a rate of 50% and a novice operator can correct that at a rate of 30%. For the recovery probability '*s*', it is assumed that a skilled operator can recognize his/her wrong action by considering the advice of the operation validation system at a rate of 70% and a novice operator can correct that at a rate of 50%.

3.4. Evaluation scenarios

The evaluation scenario comprises the occurrence of SGTR with the common cause failure (CCF) of pressurizer pressure sensors in a Westinghouse 900MWe-type pressurized water reactor NPP; in the Republic of Korea, Kori 3&4 and Younggwang 1&2 NPPs are this type of plant. The simulator that we used is a compact nuclear simulator (CNS) [24], which was initially developed in 1988 by Korea Atomic Energy Research Institute (KAERI) and Studsvik, Inc., and was recently renewed by KAERI in 2003. From the simulation, it was found that the diverse plant protection system (DPPS) will not generate an automatic reactor trip signal and that the engineered safety feature actuation system (ESFAS) will not generate an automatic safety injection actuation signal due to the CCF of pressurizer pressure sensors. In this situation, operators have to correctly understand the state of the plant as well as manually actuate reactor trip and safety injection.

In the evaluation scenario, operators are required to perform two operation tasks against two evaluations. The operation task in the first evaluation is to trip the reactor manually and the operation task in the second evaluation is to isolate the failed SG. Under these conditions, the failed pressurizer pressure sensors cause the DPPS to fail to trip the reactor automatically. Therefore, operators have to diagnose the current status correctly and trip the reactor manually. Operators also have to identify the failed SG and isolate it. Evaluations are performed for the following seven cases:

Case 1: No decision support system is used and the indicator type is analogue.

Case 2: The indicator type is digital.

Case 3: The indicator type is analogue and the fault diagnosis system is used.

Case 4: The indicator type is digital and the fault diagnosis system is used.

Case 5: The indicator type is analogue and a computerized procedure system is used.

Case 6: The indicator type is digital, and the fault diagnosis system and the computerized procedure system are used.

Case 7: The indicator type is digital, and the fault diagnosis system, the computerized procedure system, and the operation validation system are used.

For all cases, HRA event trees are made, and examples are shown in Figs. 5 and 6. For the next step, BBN models for seven cases are constructed based on the HRA event trees. Numerous nodes represent factors for humans, cognitive processes and decision support systems, and their relationships are represented by arcs among the nodes. For example, the BBN model for Case 7 is shown in Fig. 8. At the bottom of the figure, there are nodes representing the plant and sensors. Nodes for performance shaping factors are in the upper left and upper right sides. There are also nodes for decision support systems and major cognitive activities.

3.5. Evaluation results

The results of the evaluations are obtained using the implemented BBN models. The evaluation results are shown in Tables 4 and 5. The values here represent the failure probabilities of the given operation tasks. For example, if a decision support system is not used in the first evaluation, the probability of situation assessment, $P(X)$, is shown in Eq. (8) for a skilled operator and the BBN model of this case is shown in Fig. 9. The final result is 0.017444, which represents the probability that a skilled operator fails to trip the reactor in the SGTR situation:

$$P(X) = \{0.005403, 0.001466, 0.992490, 0.000641\}. \tag{8}$$

As no commission error is considered in the first evaluation, the operation validation system is also not considered. This explains why the result values for Cases 6 and 7 are identical in the first evaluation. The effect of the operation validation system is reflected in the result of the second evaluation; the result value for Case 7 is less than that of Case 6.

To briefly summarize the results, it is shown that decision support systems are helpful for reducing the operation failure probabilities of operators. According to the results, when a decision support system is not used, the failure probability of a reactor trip operation is 0.017444. However, when four decision support systems supporting major cognitive activities are used and the reliabilities of the fault diagnosis system and the operation validation system are both 99.9%, the failure probability of a reactor trip operation is decreased to 0.004988. Thus, the failure probability is reduced by 71.4%. For a novice operator, the failure probability without a decision support system is 0.023344, but with all decision support systems having 99.9% reliabilities the failure probability is 0.006990. Here, the failure probability is reduced by 70.1%. For a failed SG isolation operation, the failure probability of a skilled operator without a decision support system is 0.022820, and that of a skilled operator with all decision support systems having 99.9% reliabilities is 0.006651. In this case, the failure probability is also reduced by 70.9%. For a

Table 4
Results of the first evaluation

Reliability of FDS and OVS	99.9%		99%		95%	
Expertise Aid type	Skilled	Novice	Skilled	Novice	Skilled	Novice
Case 1	0.017444	0.023344	0.017444	0.023344	0.017444	0.023344
Case 2	0.014512	0.018478	0.014512	0.018478	0.014512	0.018478
Case 3	0.013964	0.018106	0.016632	0.022121	0.029161	0.038133
Case 4	0.011974	0.013962	0.014180	0.018041	0.026337	0.034012
Case 5	0.013897	0.019738	0.013897	0.019738	0.013897	0.019738
Case 6	0.004988	0.006990	0.009477	0.013256	0.019453	0.027181
Case 7	0.004988	0.006990	0.009477	0.013256	0.019453	0.027181

Table 5
Results of the second evaluation

Reliability of FDS and OVS	99.9%		99%		95%	
Expertise Aid type	Skilled	Novice	Skilled	Novice	Skilled	Novice
Case 1	0.022820	0.028994	0.022820	0.028994	0.022820	0.028994
Case 2	0.019854	0.024035	0.019854	0.024035	0.019854	0.024035
Case 3	0.017915	0.023238	0.020583	0.027431	0.030303	0.041194
Case 4	0.015202	0.018497	0.019656	0.024696	0.029555	0.038473
Case 5	0.017910	0.024128	0.017910	0.024128	0.017910	0.024128
Case 6	0.008239	0.011557	0.012725	0.017800	0.022693	0.031674
Case 7	0.006651	0.010370	0.011158	0.016631	0.021205	0.030568

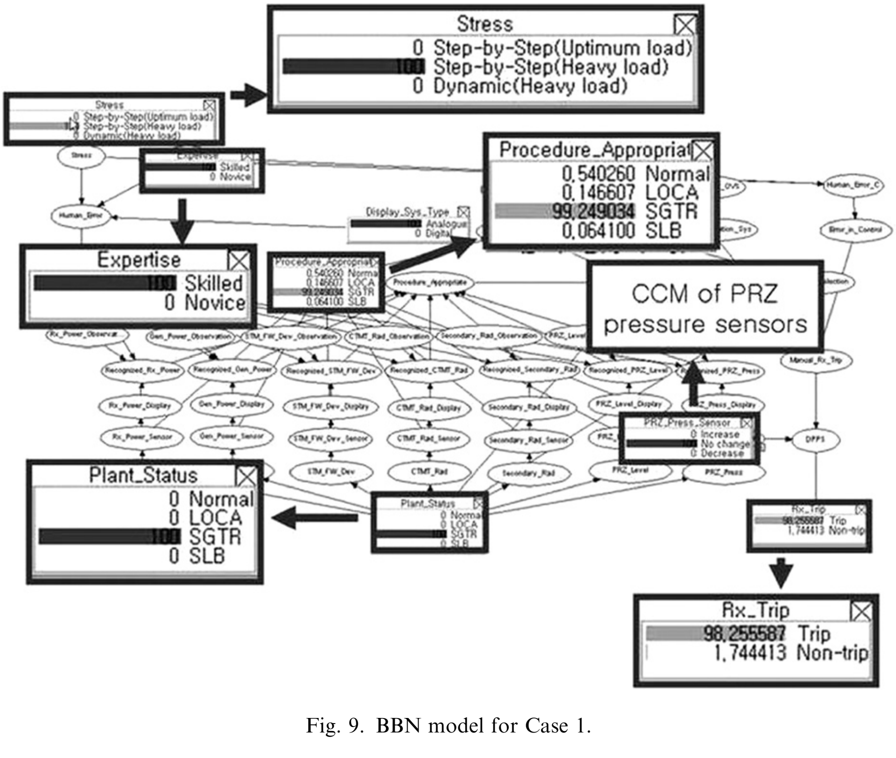

Fig. 9. BBN model for Case 1.

novice operator, the failure probability without a decision support system is 0.028994; with all decision support systems having 99.9% reliabilities it is 0.010370. The failure probability is reduced by 64.2%.

Moreover, if the fault diagnosis system and the operation validation system have 99% reliabilities, the decision support systems yield good results. In the first evaluation for a reactor trip operation, the failure probability of a skilled operator is reduced by 45.7% and that of a novice operator is reduced by 51.1%. In the second evaluation for a failed SG isolation operation, the failure probability of a skilled operator is reduced by 43.2% and that of a novice operator is reduced by 42.6%. However, if the reliabilities of the decision support systems are 95%, degraded results are obtained. In this case, the integrated decision support system increases the failure probabilities in almost all cases. The results show the reliability of a decision support system is very important in terms of enhancing the operator's performance.

The results of both the first evaluation and the second evaluation reflect good outcomes of the decision support systems. According to these results, the effect of the decision support systems is greater for less-skilled operators than for highly skilled operators. In the first evaluation for 99.9% reliability, the failure probability decrement by the decision support systems is 0.012456 for skilled operators, and that for novice operators is 0.016354. The result from the second evaluation is similar.

The results also show that the effect of the independent decision support systems is less than that of integrated decision support systems based on cognitive activities. The effect of a decision support system can be regarded as the difference between the result of the case for the decision support system and that of Case 1, as Case 1 does not include a decision support system. In the first evaluation for 99.9% reliability, the sum of the effect of the digital indicators, the effect of the fault diagnosis system, and the effect of the computerized procedure system is 0.009959 for a skilled operator. Additionally, the effect of the integrated decision support system including the digital indicators, the fault diagnosis system, and the computerized procedure system is 0.012456 for the same case. This suggests that it is possible to obtain better human performance by integrating decision support systems based on operator cognition.

4. Summary and conclusion

For advanced MCRs that have fully digitalized and computerized systems, improving HMIs and developing a decision support system can be a solution to the problem of human error. It is very important to design highly reliable decision support systems in order to adapt them in actual NPPs. In addition, to evaluate those decision support systems and validate their efficiency and reliability is as important as to design highly reliable decision support systems. There is research that focuses on evaluations regarding decision support systems for operators that evaluates the decision support systems using various methodologies and factors.

The target system of this work is an operation advisory system that supports the cognitive activities of advanced MCR operators underlying ATHEANA. The operation advisory system is a type of integrated decision support system for advanced MCRs based on the human cognitive process. In this work, the BBN is used as a basic method to estimate the effect of the target system. In order to construct the BBN model, the HRA event tree is used. To briefly review the results, they show that decision support systems are helpful for reducing the operation failure probabilities of operators. According to the results, the effect of the decision support systems is greater for less-skilled operators than for highly skilled operators. The results also show that the effect of independent decision support systems is less than that of integrated decision support systems, suggesting that it is possible to obtain better human performance by integrating decision support systems based on the cognitive activities of the operator.

This paper has limitations because the suggested model is at a feasibility study stage. For more reliable and credible evaluation results, the models should be extended in order to consider group operations, more indicators, and more situations. The evaluation results in this paper were obtained using theoretical methods, and the results are much affected by the assumptions and the data used, such as the HEP values. Several viable results were obtained from the evaluations. However, not only theoretical methods but also experimental methods are necessary for more reliable and replicable results. Thus, experimental evaluations including objective and subjective methods would make for worthwhile further study.

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