Development of Operator Response Time Model for DICE (Dynamic Integrated Consequence Evaluation)

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Abstract: Integrated Deterministic-Probabilistic Safety Assessment (IDPSA) which can facilitate the time dependency has been actively executed. IDPSA can provide explicit consideration for dependencies among systems, components, plant states, and delayed times for the operator's actions based on a continuous or discrete-time basis. Discrete Dynamic Event Tree (DDET) methodology has been generally used in IDPSA research. In Kyung Hee University, DICE (Dynamic Integrated Consequence Evaluation), a dynamic reliability analysis tool using DDET, was developed as a supporting tool for DPSA research. The diagnosis module, one of the modules in DICE, monitors plant status and controls plant states by commanding operator actions through the combination and logic of physical variables. It is expected that operator actions such as success, omission, or commission would make huge variance along with an accident scenario. Therefore, as a presentative application, DICE attempts to investigate such variance in a systematic way. In this study, the operator model to provide action timing was developed on the basis of SPAR-H (Standardized Plant Analysis Risk Human Reliability Assessment) and the method how to use the operator model in DDET was proposed.

1. INTRODUCTION

Probabilistic Safety Assessment (PSA) evaluates the safety of complex engineering systems. For a long time while evaluating the safety, the conventional PSA, executed with ET and FT, has provided great help in evaluating the safety of nuclear power plants. However, the conventional PSA has difficulties analyzing temporal, inter-complex dependencies, etc. In addition, there is a potential weak point that it is difficult to discover unknown scenarios[1,2].

In order to overcome these limitations, Integrated Deterministic Probabilistic Safety Assessment (IDPSA)which can facilitate the time dependency and uncertainty analysis has been actively carried out[3,4]. IDPSA can provide explicit consideration for dependencies between systems and components (e.g., time-dependent common cause failures) and operator's actions based on a continuous or discrete-time basis.

Since the IDPSA method performs both deterministic and probabilistic methods in real-time, it is possible to discover unknown scenarios that have not been considered in the existing analysis or to perform sensitivity analysis according to plant physical variables[5].

DICE developed by Kyung Hee University, as one of the IDPSA tools, consists of a physics module, a diagnostic module, a reliability module, and a scheduler that controls the three modules. Also, depending on the user's needs of aspect, two methods of calculation can be selected: single-branch mode or multi-branch mode. As the major function of the DICE single-branch mode is to discover the unknown scenarios, it is necessary to vary the operator response time to increase the degree of freedom for the scenario.

This paper, there is introduced the overall explanation of DICE and the development of the operator response time model.

2. INTRODUCTION TO DICE

2.1. Structure of DICE

As shown in Fig. 1, there is a composition of DICE and consists of a physics module that performs physical analysis such as thermal-hydraulic analysis for a nuclear power plant, a diagnosis module that monitors branching conditions at each time step, a reliability module that supports quantification of branches and determines failure mode of components using reliability information, and scheduler that manages an overall simulation of DICE by the information exchanges between each module and divide the branch trough the DDET method[6-8].

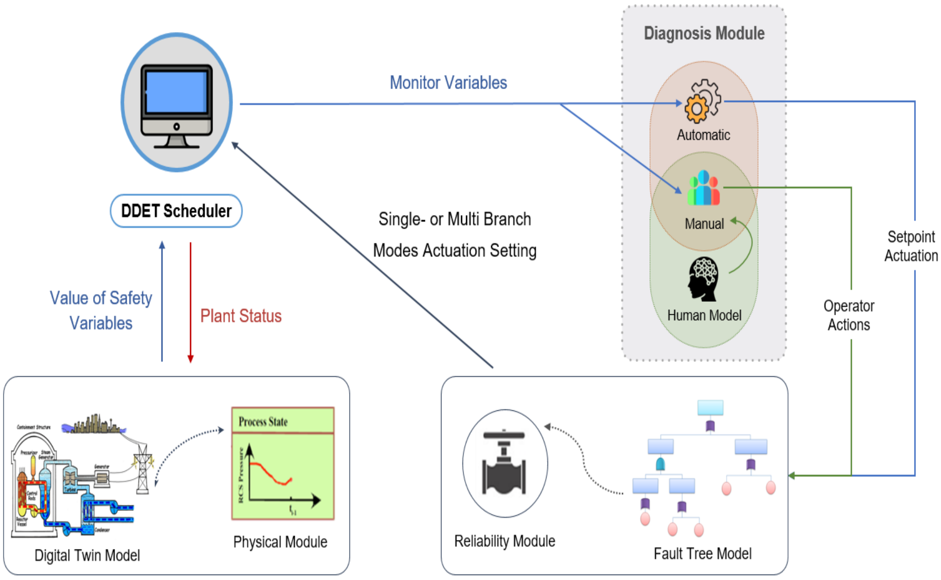

Fig 1. Schematic diagram of DICE

2.1.1 Scheduler

The scheduler is an important module of the DICE, it is responsible for exchanging information between individual modules, and based on that information, processes the simulation according to whether a branch occurs in the event tree. Also, the scheduler decides to continue or terminate the simulation according to the state of the simulation results. The DDET method is a method in which the user does not set the branch point in advance, but sets the branch point by applying the results of the real-time physical model. It may produce the same result as the existing event tree, and may produce a different result by reflecting accidental factors (e.g., running failure, human action, etc.).

2.1.2 Physical Module

The physical module is responsible for the physical analysis of the nuclear power plant used for accident analysis and generally uses the thermal-hydraulic accident analysis code to simulate the behavior of the system over time in case of an accident. As the simulation progresses, the variables resulting from the analysis of the plant model are transmitted to the scheduler in real-time, and conversely, physical behavior is implemented by receiving the state information of devices in each event sequence from the scheduler. Currently, DICE is equipped with MARS-KS 1.5, and MELCOR 2.x is additionally being connected.

2.1.3 Diagnosis Module

The diagnosis module determines whether or not the power plant equipment operates due to automatic or manual action during the simulation process and manages branching rules. Diagnostic modules are divided into automatic and manual diagnostic modules according to the type of operation. The automatic diagnosis module deals with branch rules for facilities that are automatically operated in the power plant, such as ESF (Engineered Safety Features) and RPS (Reactor Protection System), and the manual diagnosis module handles Emergency Operation Procedure (EOP) or Severe Accident Management Guideline (SAMG), depending on the scenarios to be analyzed.

2.1.4 Reliability Module

When the branch occurrence is determined from the results of the diagnostic module, the reliability module calculates the branch probability by considering the failure mode of the system and the device

constituting each branch and returns the result to the scheduler. In addition, the corresponding module differs in functions performed according to the simulation modes, called multi-branch mode and single-branch mode, of the scheduler. In the multi-branch mode of the scheduler, the reliability module played a major role in calculating branch probabilities using the fault tree and operator behavior diagnosis/performance probabilities.
However, in a single branch mode in which a single scenario is deployed repeatedly, the reliability module plays a role in determining conditions such as device failure or recovery by comparing random numbers generated at each time step with reliability data.

2.2. Two Methods for DICE process

2.2.1 Multi-Branch Method[9]

As shown in Fig. 2, an algorithm for multiple branches. In the multiple branch mode, information about the physical variables of the physical module is transmitted by the diagnostic module, and whether there is a satisfactory branch rule or not is confirmed. If a satisfactory branch rule is found by automatic or manual diagnosis, prepare to be divided into already registered branch rules. At this time, if there is a situation where the equipment to be operated fails or the equipment to be failed is restored, several branches are generated in consideration of the situation.

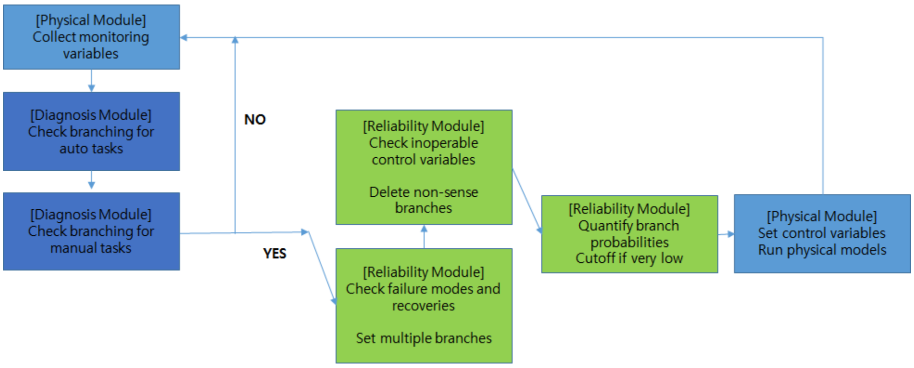

Fig 2. Algorithm for Multi-Branch Mode

2.2.2 Single-Branch Method[9]

On the other hand, Figure 3 shows a single branch mode is shown. The process of performing the diagnostic module by receiving the physical module monitoring variable is the same as the multiple branch mode. Even if the branch condition is satisfied, the single branch is maintained one path without generating other divided branches such as multi-branch. The meaning of maintaining a branch is to check the state of the equipment at the time when a change in the physical model must occur and reflect it in the control variables of the physical model as it is.

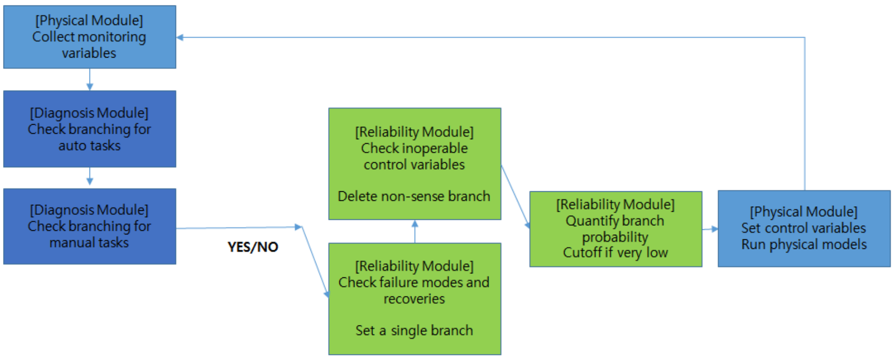

Fig 3. Algorithm for Single-Branch Mode

3. OPERATOR RESPONSE TIME MODEL

3.1. Needs

In the case of DDET, a branch is created as the result of the physics module that changes in the plant status, so it affects branch creation depending on whether the operator's action time is changed. By giving such variability, it is possible to discover unknown scenarios that have not been confirmed by existing analysis. That is, the operator model can improve the degree of freedom for scenarios in the IDPSA, so this paper deals with the development of a stochastic model that can provide operator response time. The developed operator model should work on the manual diagnosis module.
To make the operator response time model on the DDET workable, the validity of the model should be proved that they must be consistent results for the human reliability assessment. Therefore, it is necessary to develop an operator response time model which can provide equivalent attributes such as Human Error Probability and Performance Shaping Factor with the existing licensed HRA methods[10].

3.2. Algorithm Development

With sharing the needs aforementioned, the operator model is developed through the method called SPAR-H (Standardized Plant Analysis Risk HRA). SPAR-H is one of the most widely performed methods for evaluating the human error of nuclear power plants[11]. SPAR-H calculates the probability of human error in diagnosis and execution by multiplying the performance shaping factor weight evaluated by experts by the Nominal Human Error Probability (NHEP).

$$HEP_{execution} = NHEP_{execution} + \prod_{i=1}^{8} PSF_{execution,i} \quad (1)$$
$$HEP_{diagnosis} = NHEP_{diagnosis} + \prod_{i=1}^{8} PSF_{diagnosis,i} \quad (2)$$
$$HEP = HEP_{diagnosis} + HEP_{execution} \quad (3)$$

As shown in Fig. 4, the operator response time model algorithm based on HEP provided SPAR-H, which can be used DDET method is presented:

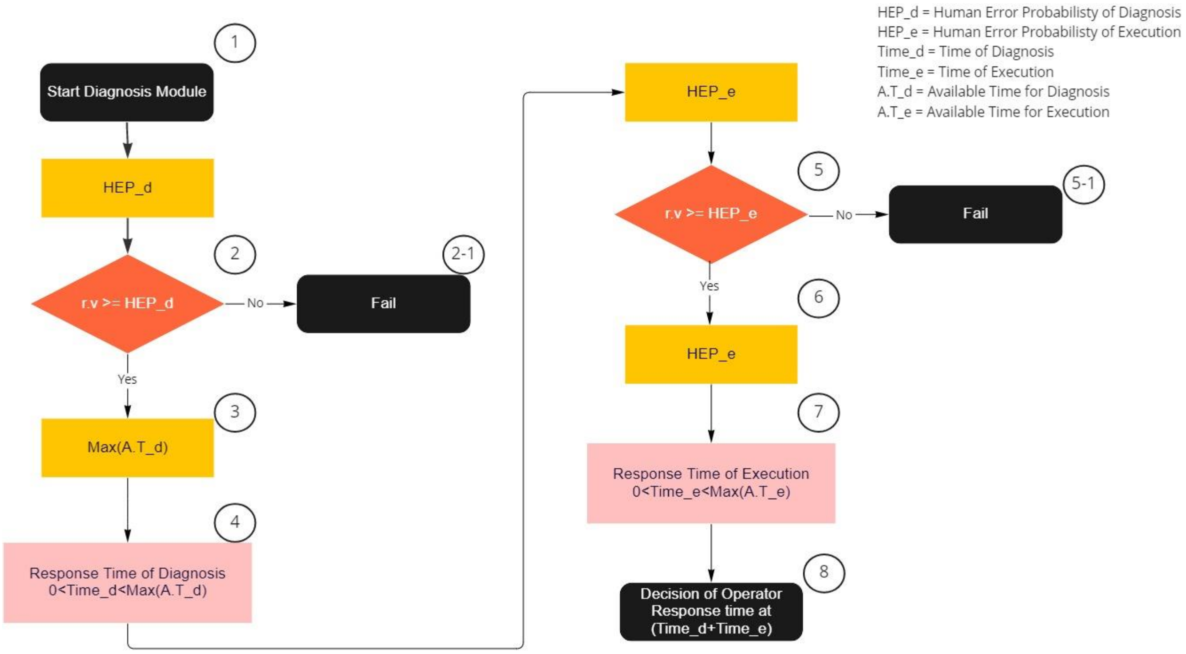

Fig 4. Algorithm for Operator Response Time Model

Step 1. When the monitoring variable of the physical module satisfies the conditions of the manual diagnosis module, the scheduler gives a command to start calculation through the operator model equipped with the manual diagnosis module. It is assumed that human error probability and operator available time data for diagnosis and performance are secured based on existing analysis data.

Step 2. When the manual diagnosis module operates, the operator judges whether the diagnosis is normal or not. Generate a random number between 0 and 1 following a specific probability distribution and compare it with the HEP for diagnosis (HEP_d). If the generated random number is greater than or equal to the probability of human error for diagnosis, it is judged that the diagnosis has been made normally. In generating random numbers, the probability distribution can be arbitrarily determined by the analyst.

Step 2-1. If the generated random number is less than the set HEP_d, the operator determines that the diagnosis has failed. Failure to diagnose means that the operator has exceeded its diagnostic time or failed to diagnose properly (that is, no operator action has been taken), so the calculation is performed without changing the physical module configuration.

Step 3. After the diagnosis is successful, the operator response time for the diagnosis shall be determined. In 1, information that is the time for operator diagnosis already exists, and the operator response time for the diagnosis can be determined by utilizing the existing data. A time range should be set by the user to determine the operator response time for the diagnosis, and the time shall be evaluated at a level proportional to the diagnosis nominal time. The minimum time taken by the driver for the diagnosis was set to 0 seconds, judging that the driver made the diagnosis immediately. A maximum time (Max (A.T_d)) of the operator response time for diagnosis(i.e., the time for the operator to check the monitoring variable and the latest diagnosis) is set as a maximum value (Max (A.T_d)) of the operator use time for the diagnosis. For example, if the operator available time for the diagnosis is evaluated as ‘Extra’, the Max (A.T_d) set the 1.5 multiple larger nominal diagnosis time.

Step 4. The operator response time for diagnosis is to determine the time (Time_d) by utilizing the random number reproduced based on the specific probability distribution for the range set in Step 3.

Step 5. After determining the diagnosis time, if the random number generated by comparing it with the random number is greater than or equal to the execution HEP, the operator is judged to have performed normally.

Step 5-1. If the generated random number is less than the HEP for the set execution, the operator determines that the execution has failed. Failure to execute means that the operator's available time for the execution is exceeded or the ordinary performance is unsuccessful, meaning that no operator action was taken. Even if the diagnosis is successful, if the execution fails, the physical module will not receive any signal and proceed with the calculation.

Step 6. After successful execution, the operator response time for the execution shall be determined. There is already information about the available time for the execution, and the operator response time for the execution can be determined by utilizing the information. A time range should be set by the user to determine the operator response time for the execution, and the response time should be evaluated at a level proportional to the execution nominal time. The minimum operator response time for the execution was set to 0 seconds after determining that the operator immediately performed it. A maximum time (Max (A.T_e)) is set as a maximum value for operator response time for execution (i.e., a time for slow diagnosis of performance after diagnosis). However, since it is confirmed in paragraph 6 that the operator response time is within the operator available time, the operator response time for execution must be within the value of the operator response time for performance.

Step 7. The operator response time for execution is to determine the time (Time_e) by utilizing the regenerated random number based on the specific probability distribution for the range set in Step 6.

Step 8. The final operator action time is transmitted to the physical module by combining the operator response time for diagnosis and execution determined in Step 4 with Step 7.

3.3. Verification for Operator Response Time Model

The operator response time model was demonstrated for primary cooling and decompression failure using low pressure safety injection in a small loss of coolant accident (SLOCA). As explained in the algorithm, the data for the HEP and operator available time level for diagnosis and execution is assumed to be ready in advance.

Table 1: Example 1 of Model Results

	Value	Result
Available Time	23 min(1,380 s)	
Diagnosis HEP	6.20E-01	
Diagnosis Available Time Level	Nominal	
Diagnosis Nominal Time	19 min(1,140 s)	
Success or Fail by comparing for Diagnosis		Success
Operator Response Time for Diagnosis		512 sec
Execution HEP	2.90E-02	
Execution Available Time Level	Nominal	
Execution Nominal Time	3min(180 s)	
Success or Fail by comparing for Execution		Success
Operator Response Time for Execution		123 sec
Operator Action Time		635 sec

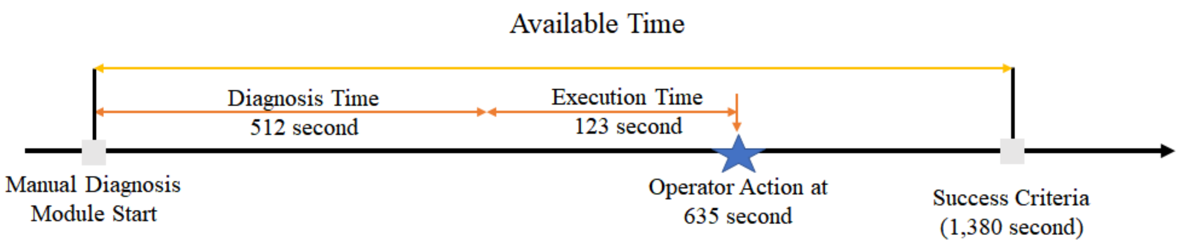

Fig 5. Timeline of Example 1

First, a random number from 0 to 1 was generated and compared with the diagnostic HEP. It turned out the diagnosis would be successful. Afterward, the range of random number generation was adjusted according to the evaluation of the diagnosis available time level. In this simulation, since it was evaluated as Nominal, the random number was generated between 0s and 1,140s to finally calculate the diagnosis time. So, the operator response time for diagnosis was set to 512 sec.
Next, the operator response time for execution was determined by calculating the same as the previous method. The operator response time for execution was set to 123 sec.
Finally, both of the diagnosis and execution were successful, and it was assumed that the operator would successfully operate the low pressure safety injection action at 635 seconds. Fig 5 shows the timeline for example 1 result.

Table 2: Example 2 of Model Results

	Value	Result
Available Time	23 min(1,380 s)	
Diagnosis HEP	6.20E-01	
Diagnosis Available Time Level	Nominal	
Diagnosis Nominal Time	19 min(1,140 s)	
Success or Fail by comparing for Diagnosis		Success
Operator Response Time for Diagnosis		1,021 sec
Execution HEP	2.90E-02	
Execution Available Time Level	Nominal	
Execution Nominal Time	3min(180 s)	
Success or Fail by comparing for Execution		Fail
Operator Response Time for Execution		-
Operator Action Time		No Action

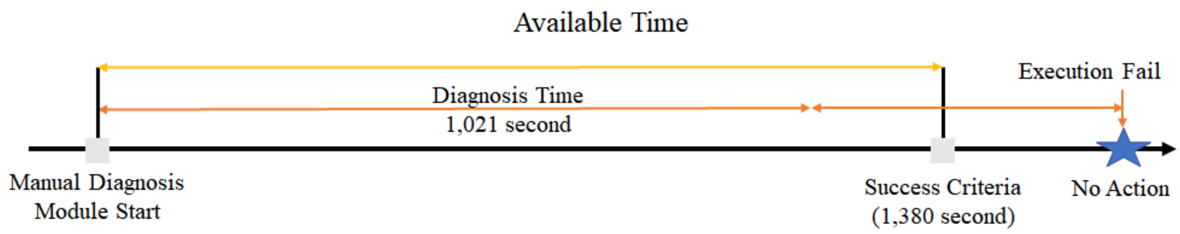

Fig 6. Timeline of Example 2

As shown in Table 2, the simulation is repeated for the same method. The operator response time for diagnosis was successfully determined at 1,021 seconds, but the execution failed due to the lower random number than that of the execution HEP. As a result, even if the operator succeeded in diagnosis, the operator did not take any action because the execution would fail. Fig 6 shows the timeline for example 2 result. It means that operator response time for execution would be over the available time or take a mistake of execution.

4. CONCLUSION

PSA has been performing effectively in risk assessment to ensure plant safety for a long time. However, there are insufficient points to consider the temporal, system dependency, human effects, etc. In order to complement this point, the IDPSA method using the DDET method has been actively discussed. In this paper, the description of DICE, an IDPSA tool, and the development of an operator model applicable to the DDET method was introduced.

By developing the operator response time model, it is expected to be possible to discover unknown scenarios and analyze other results for existing evaluations due to the variation in operator response time.

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