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Development of a Monte-Carlo Based Operator Model for DICE(Dynamic Integrated Consequence Evaluation)

Dohun Kwon , Sejin Baek, Gyunyoung Heo*
Kyung Hee University, Yongin-si, Gyeongi-do, 17104, Korea
**Corresponding author: gheo@khu.ac.kr*

1. Introduction

Probabilistic Safety Assessment (PSA) has been used to evaluate the risks for complex engineering systems such as Nuclear Power Plants (NPPs) using the combination of Fault Trees (FTs) and Event Trees (ETs). However, the conventional approaches (i.e., fixed headings with a binary binning) are difficult to consider dynamically nonlinear processes or temporal dependencies, so unknown scenarios are rarely observed[1,2].

In order to overcome these limitations, Integrated Deterministic Probabilistic Safety Assessment (IDPSA) which can facilitate the time dependency has been actively carried out. The 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. The necessities for IDPSA research have been known for a long time ago. Discrete Dynamic Event Tree (DDET) methodology was generally used in many other IDPSA tools[3]. In Korea, DICE (Dynamic Integrated Consequence Evaluation) which is a dynamic reliability analysis tool using DDET, was developed as a supporting tool for IDPSA research. Previous studies for DICE have been focused on the algorithmic structure, the branching conditions, and the result of simplified models[4].

The first version of DICE has utilized a rather deterministic approach method, so called multi-branch mode, to divide branching at predetermined point in the probabilistic distribution. Besides, the temporal dependency or variability of human errors, one of the major event causes of NPPs, could not be sufficiently demonstrated with conventional multi-branch mode.

In this paper, we introduce a new DDET algorithm, called single-branch mode, which may be effectively improved in discovering unknown scenarios caused by operator's temporal behavior. The single-branch mode was operated by Monte Carlo simulation and detailed features for single-branch mode are mentioned in Section 3-1. To support this algorithm, an operator model which is also based on Monte Carlo simulation was developed and coupled with DICE. Currently, this can handle some factors of the Standardized Plant Analysis Risk-Human Reliability Analysis(SPAR-H)

2. Explain for branching methods

As shown in Fig. 1, DICE consists of physical module that performs thermal-hydraulic analysis, automatic/manual diagnostic module that monitors branching condition at each time step, reliability module which 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[4].

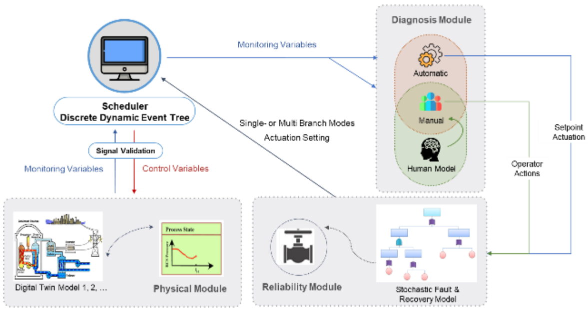

Fig. 1. DICE Structure

DICE operates multi-branch and single-branch mode depending on the setting of the scheduler.

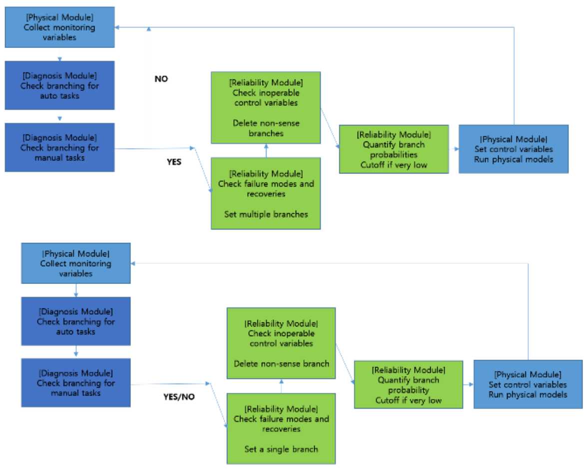

Fig. 2. upper: DICE multi-branch algorithm,
lower: DICE single-branch algorithm
(blue: same algorithm, green: different algorithm)

In Fig. 2, both methods have the same mechanism for judging the satisfaction of the branching conditions based on the physical module's monitoring variables, and then, the diagnosis module checks the branching conditions for automatic/manual tasks, and finally, the reliability module confirms the system status (e.g., run, stand-by, failure, etc.) and transfers the necessary control variables to the physical module.

However, the methods differ in the processing algorithm for the scenario. In the multi-branch mode, if a branching condition is satisfied, the scenario will be divided into predetermined branches. As a result, only one iteration of simulation can develop with a number of scenarios. In single-branch mode, although the branching condition is satisfied, the branch is consistently going straight only 'one' exiting scenario, which means it does not create any other branches. Therefore, it requires many iterations of simulation, whereas the quantification is easy due to summation for damages(e.g., core damage).

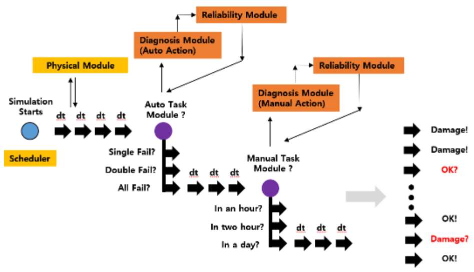

Fig. 3 DICE multi-branch process

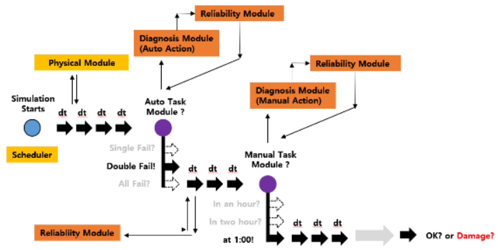

Fig. 4 DICE single-branch process

In Fig. 3, when the branching conditions are satisfied, the multi-branch mode divides the branch into predetermined branches and sets the control variables of the physical module by confirming the stand-by, failure, or recovery of the system status. This determinates equipment failure only at branching points.

However, as shown in Fig. 4, regardless of the satisfaction, until one branch is terminated, DICE checks the system status by comparing random numbers and system failures(e.g., component failure, human error, etc.) at each time step and adjusts control variables. The single-branch mode is distinguished from a viewpoint of the evaluation of equipment failure and operator action.

The multi-branch mode has the weaknesses that preset the number of branch cases, but the number of simulations is optimized due to branch calculations are performed at once. In the case of the single-branch mode, there is a disadvantage that the number of simulations must be numerous iterations, but there is a benefit of discovering unknown scenarios through dynamic components. As a result, a number of single-branch simulation results can asymptotically approach to the same results as multi-branch simulation results, which is similar to 'the law of large numbers.'

3. Methodology

3.1 Necessity for dynamic operator model of single-branch mode

The diagnosis module can be sorted into automatic action and manual action. If the branching conditions are satisfied, the automatic action generates branches according to the system status without operator's action. The manual action progresses branches depending on operator's action.

Although prior research developed an operator model, which was based on artificial intelligence [5], a new need was emerged for the compliance with existing regulatory requirements related with the operator models. Thus, we developed a probability distribution for operator's action by fitting the method of SPAR-H so that it can provide action timing using Monte Carlo simulation.

The multi-branch model is restricted for operator's degree of freedom due to the preset branching. But in the case of the single-branch mode, system status and human error are dynamically changed every time step by comparing random numbers, so the same manual action branches can make different results.

3.2 Methodology for dynamic operator model

The dynamic operator model was developed by using the SPAR-H method and Monte-Carlo simulation. The SPAR-H method was developed for the quantification of the Human Error Probability (HEP) based on eight Perform Shaping Factors (PSFs) evaluated in expert opinion[6]. An overall HEP is multiplied by nominal HEP(NHEP) and PSF such as shown in equation (1).

$$HEP = NHEP(1) \cdot \prod_{i=1}^{8} \mathrm{PSF}_i \qquad (1)$$

In previous research for a dynamic HRA, there was a case that the PSF multiplier was fitted to a proper probability distribution using the SPAR-H method. The method for matching the distribution was maximization likelihood estimate (MLE) algorithm. For each distribution, an Akaike information criterion (AIC) was applied along with the distribution parameters. Table I contains the results of the distribution for each PSFs[7,8]. The distributions for the PSFs in Table I are limited to only action tasks which are some scenarios for normal operation for NPP.

Table I: PSFs fitted to a continuous distribution(P_1: log-mean, P_2: log-standard deviation, S.E.P_1: standard error for P_1, S.E.P_2: standard error for P_2)

PSF_i	P_1	P_2	S.E.P_1	S.E.P_2
Available Time(1)	0.034	0.712	0.031	0.022
Complexity(2)	0.049	0.2	0.009	0.006
Ergonomics / Human Machine Interface(3)	0.152	0.601	0.026	0.018
Experience /Training(4)	0.088	0.327	0.014	0.01
Fitness for Duty(5)	0.025	0.2	0.009	0.006
Procedure(6)	0.229	0.693	0.029	0.021
Stress / Stressors(7)	0.112	0.265	0.011	0.008
Work Processes(8)	0.282	0.649	0.026	0.018

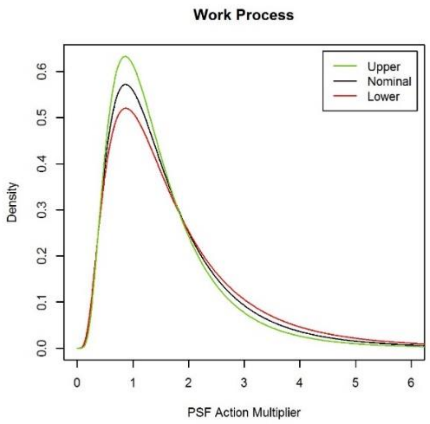

Fig. 6. Example for 'Work Process' multiplier distribution applied to PSF_8

Taking the log-normal distribution for 'work process' PSF in Table I and implementing a 99% interval on the distribution parameters results in Fig. 6.

We will make the dynamic operator model fitted the HEP distribution by referring previous research. The model has to be made of the PSFs and modified to the distribution by using mathematical methodologies. The developed model should be equal to the SPAR-H value. Fig. 7 shows an algorithm for the operator model of single-branch mode. When a condition for a manual action is met, a random number made of Monte Carlo simulation calculates an available time which is fitted the HEP distribution, and then the success/failure of operator action is determined.

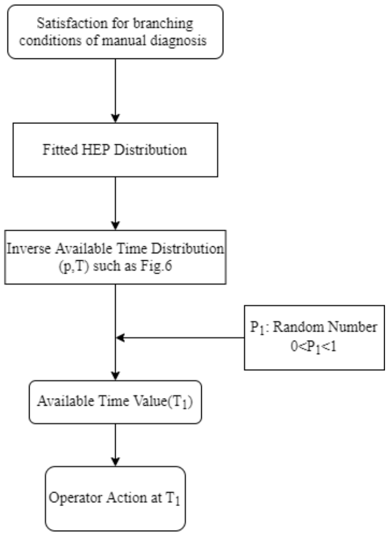

Fig. 7. Mechanism for dynamic HRA method

4. Conclusions

In this study, we introduced two modes for DICE, a dynamic reliability analysis tool. We described the need for the single-branch mode and the required methodology for the single-branch mode on development. In particular, in the single-branch mode, manual action, that is an operator model, needs to be developed in compliance with the SPAR-H method.

For next research, the DICE will be carried out after the dynamic operator model is embedded in the diagnosis module of DICE.

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