Bayesian Belief Network Approach for Human-Induced Unplanned Trips during Startup and Shutdown Operation

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1. Introduction

According to the Operational Performance Information System for Nuclear Power Plants (OPIS) of the Korea Institute of Nuclear Safety (KINS), 20% of unplanned trips incidents by human error were caused by human operators during startup and shutdown operations over a recent 10-year period [1]. Since unplanned trips can impair the safety of nuclear power plants (NPPs) or threaten important safety functions, it is necessary to reduce human error through human reliability analysis (HRA) as a structured approach used to identify potential human failure events (HFEs) and estimate the probability of those errors.

Most HRA methods such as Techniques for Human Error Rate Prediction (THERP) [2], and Human Cognitive Reliability Correlation (HCR) [3] derive HFEs that induce the initiating events or core damage following a trip and conservatively evaluate human error probabilities (HEPs) for those events. However, since most of the tasks related to the startup and shutdown operations are routine tasks that can lead to unplanned reactor trips, the startup and shutdown operations should be evaluated by summing all the HEPs of the unplanned trip-induced tasks. So, if the existing HRA methods are applied to evaluate the startup and shutdown operations, overestimated HEPs of startup and shutdown operations will be obtained.

To overcome the difficulties of applying the existing HRA methods, Bayesian belief network (BBN) with advantageous for taking an event that occurred and predicting the likelihood that any one of several possible known causes was the contributing factor are used. To construct the BBN model, the quantification framework for startup and shutdown operations is developed based on THERP and Korean standard HRA (K-HRA) [4] methods. In this paper, the occurrence probability of human-induced unplanned trips and the influence of the task on unplanned trips are evaluated based on the developed BBN model. In addition, to demonstrate the occurrence probability of unplanned trips estimated from the BBN model, the probability estimated from the model was compared with actual incidents of unplanned trips.

2. Methods and Results

Fig. 1 shows the flowchart of a new HRA methodology for startup and shutdown operations, developed starting with a general operating procedure (GOP) for startup and shutdown operations. As shown in Fig. 1, the methodology is divided into qualitative and quantitative analyses. Qualitative analysis is detailed in [5]. The quantitative analysis is subdivided into three steps: Task HEP quantification, BBN model construction, and BBN-based quantitative evaluation. In this section, these three steps are described.

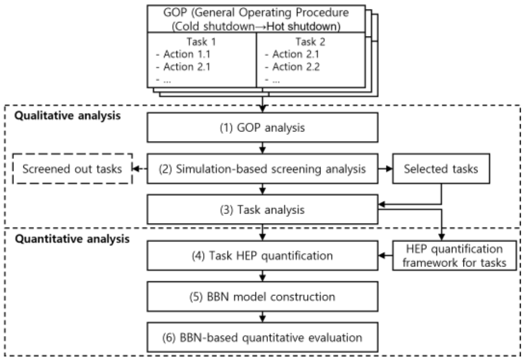

Fig. 1. Flowchart of the HRA methodology for startup and shutdown operations

2.1 Task HEP Quantification

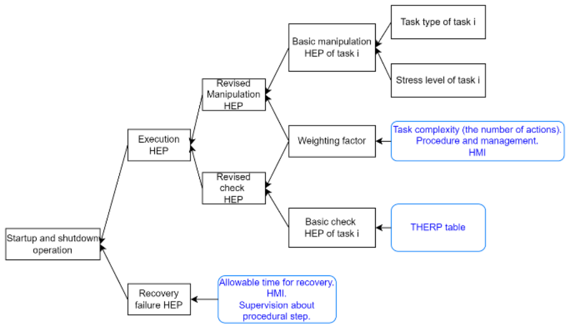

Fig. 2. Quantification framework to quantify the HEPs of the startup and shutdown operation tasks

The task HEP quantification step quantifies the HEPs of tasks selected via the qualitative analysis. To estimate the HEP of a task, a quantification framework for startup and shutdown operations is developed, as shown in Fig. 2. Since startup and shutdown operations are conducted following pre-planned tasks in accordance with predetermined procedures, the diagnosis and decision-making for recognizing problems and determining countermeasures does not play a major role. Therefore, in this framework, only execution errors are considered assuming that diagnosis and decision-making errors are negligible. Also, the execution errors are subdivided into manipulation and check errors because there are many manipulation and check actions in each task that can cause unplanned trips. In real cases, there are incidents in which unplanned trips occurred due to failure to control the water level of the steam generator or omission of checking the initial conditions during the startup and shutdown operations.

Detailed HEP quantification for a startup and shutdown operation task is calculated using the following equations:

$$Revised\_HEP_{manip}(i) = Basic\_HEP_{manip}(i) \times w_i(PSFs) \quad (1)$$
$$Revised\_HEP_{check}(i) = Basic\_HEP_{check}(i) \times w_i(PSFs) \quad (2)$$
$$HEP_{exec}(i) = Revised\_HEP_{check}(i) + Revised\_HEP_{check}(i) \quad (3)$$
$$HEP_{startup\ and\ shutdown\ operation} = \sum(HEP_{exec}(i) \times HEP_{rec}(i)) \quad (4)$$

where $Basic\_HEP_{manip}(i) = f$(task type (i), stress level (i)), $Basic\_HEP_{check}(i) = f$ (THERP table), $w_i = f$(task (i) complexity in terms of manipulation and check actions), procedures and administrative control (i), HMI (i)), and $HEP_{rec}(i) = f$(available time for recovery (i), HMI (i), supervision about procedural steps (i)).

The task type (i), stress level (i), weighting factor (w_i), and recovery failure HEPs of task i ($HEP_{rec}(i)$) are determined using the PSFs and decision trees used in the K-HRA method. And estimated HEPs of checking quantitative information or confirming the component state in THERP table are used for basic check action HEP of task i ($Basic\_HEP_{check}(i)$) because the estimated HEPs of check actions are not provided in K-HRA method, and the K-HRA method is based on THERP.

2.2 BBN Model Construction

BBN model for startup and shutdown operations is constructed based on the quantification framework in Fig. 2. The Fig. 3 shows a simplified schematic BBN model for startup and shutdown operations. The nodes composing the BBN model are PSFs, manipulation and check actions, task in procedure, recovery failure HEPs, and plant status. In Fig. 3, the A_n node indicates the PSFs, X_m indicates the manipulation actions, Y_m indicates the check actions, Z_m indicates the tasks, and R_l indicates the recovery failure HEPs. The A_n nodes have multi-state variables (e.g., high, medium, low) or binary state variables (i.e., yes, no). The X_m, Y_m, Z_m, and R_l nodes have binary state variables: fail ($x_{m1}, y_{m1}, z_{m1}, r_{l1}$), success ($x_{m2}, y_{m2}, z_{m2}, r_{l2}$). Similarly, the plant status node has binary state variables (i.e., normal, unplanned trip).

In the BBN model developed, the node relationships are a form of conditional probability and are represented by arrows. The conditional probability is calculated based on the quantification framework in Fig. 2 and inserted into the corresponding section of the node probability table in the BBN model. Also, to express the dependency between the tasks, it is assumed that the previous task affects the manipulation and check action of the subsequent task. For example, if task Z_1 and Z_2 have dependencies in Fig. 3, Z_1 is linked to manipulation(X_2) and check(Y_2) of Z_2 and conditional probability is calculated using the equations for conditional probabilities of failure on a subsequent task, given failure on the previous task, for different levels of dependence in THERP.

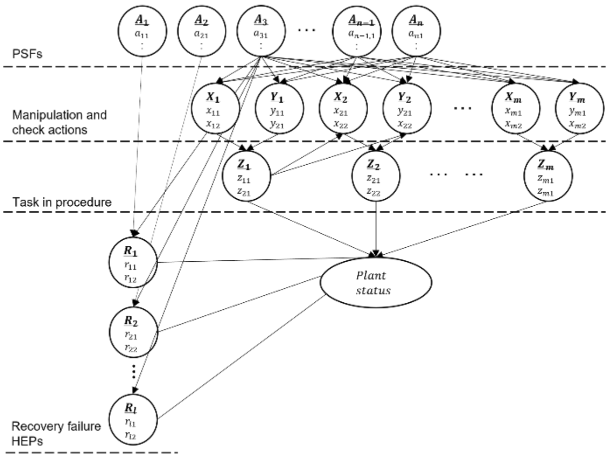

Fig. 3. Simplified schematic of the developed BBN model

2.3 BBN-based Quantitative Evaluation

In this step, quantitative evaluations of the startup and shutdown operations are conducted with the BBN model constructed in the previous step. First, the occurrence probability of human-induced unplanned trips during startup and shutdown operations is evaluated using the BBN model developed. Second, the influence of the tasks on human-induced unplanned trips is quantitatively evaluated.

2.3.1 Occurrence probability evaluation of unplanned trips

Before the BBN-based quantitative evaluation, the tasks that induce the unplanned trips and their PSFs level were determined from the qualitative analysis in Fig. 1. The tasks are shown in Fig. 4 as a 3keymaster generic pressurized water reactor simulator test procedure, developed in Western Service Corporation (WSC) [6]. A total of 11 tasks corresponding to operational mode 2 of startup operation were selected.

To calculate the occurrence probability of unplanned trips through the BBN model developed, some PSF levels were assumed as follows:

1. 'HMI', 'Procedure and administrative controls' PSFs were assumed to be 'medium'
2. 'Supervision about procedural steps' and 'requirement of information record' PSFs were assumed to be 'yes'.
3. The task type and stress level in the startup and shutdown operations were assumed to be 'step-by-step' and 'optimum', respectively. For these assumptions, the $Basic\_HEP_{manip}$ was 0.005 from the decision tree in the K-HRA method. And the

$$\Pr(human - induced\ unplanned\ trips) = \frac{Number\ of\ unplanned\ trips\ caused\ by\ operators}{\sum_i^n Number\ of\ startup\ and\ shutdown\ operations\ for\ NPP\ unit_i} \quad (5)$$

$Basic\_HEP_{check}$ was assumed to be 0.001 from the THERP.

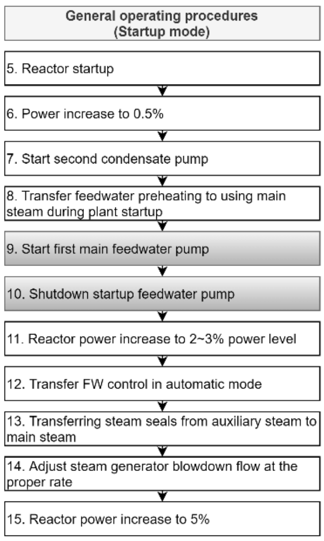

Fig. 4. The tasks selected from the qualitative analysis [5]

By applying the above assumptions to the BBN model, the occurrence probability of unplanned trips was evaluated to be 0.00549.

Also, to demonstrate the occurrence probability from the BBN model, this value was compared with the occurrence probability estimated from the actual incidents of unplanned trips. To estimate the probability from the actual incidents, information on the number of overhaul and unplanned trip incidents over a 10-year period (2003-2012) was investigated from the Korea Hydro & Nuclear Power website and OPIS, assuming the equation (5) to calculate the probability of unplanned trips from actual events. From the investigation, a total of 147 startup and shutdown operations were performed, and 4 incidents occurred over the period.

According to equation (5), the occurrence probability was estimated to be 0.0272. Since this probability reflects four operational modes of the startup and shutdown operations in contrast to the probability estimated from the BBN model to reflect the tasks of one operational mode in the qualitative analysis [5], there is no significant difference in the probabilities by two methods, which demonstrates that the developed BBN model is appropriate.

2.3.2 Influence evaluation of operator tasks on unplanned trips

To estimate the influence of the tasks on human-induced unplanned trips, the failure probability of each task was evaluated by setting the plant status node to 100% unplanned trips in the BBN model. As an evaluation result shown in Table 1, task 12 had the greatest impact at 54.59% when an unplanned trip occurred and task 8 had the second-highest impact with 40.23%.

These quantitative evaluation results of the task impact can help in selecting the dominant contributor that requires active evaluation and management to reduce human error.

Table I: Influence evaluation of the tasks

Procedure	Failure probability of tasks
Task 5	0.01099
Task 6	0.0025
Task 7	0.003
Task 8	**0.4023**
Task 9	0.06018
Task 10	0.05574
Task 11	0.0025
Task 12	**0.5459**
Task 13	0.003
Task 14	0.003
Task 15	0.003

3. Conclusions

This paper proposed a BBN approach method for human-induced unplanned trips during startup and shutdown operation of NPPs because of difficulties in applying the existing HRA methods to startup and shutdown operations. The BBN model is constructed to evaluate the occurrence probability of human-induced unplanned trips during startup and shutdown operations based on the quantification framework developed in this paper. The BBN-based quantitative evaluation result of the occurrence probability of unplanned trips was compared with the occurrence probability estimated from the actual incidents over a 10-year period in Korean NPPs. Moreover, the impact of the tasks that can cause unplanned trips was quantitatively evaluated in helping to select dominant contributors.

For more credible and reliable evaluation, in further study, more PSFs such as safety culture, organizational factors, and interdependency between the PSFs should be considered.

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