Multi-dimensional Dependency Analysis for Human Interaction in Multi-unit Scenarios

Gayoung Park [a], Awwal M. Arigi [a], Jonghyun Kim [a*]
[a]*Department of Nuclear Engineering, Chosun University, 309 Pilmun-daero, Dong-gu, Gwangju 501-709, Republic of Korea*
[*]*Corresponding author: jonghyun.kim@chosun.ac.kr*

1. Introduction

As a result of the Fukushima nuclear power plants (NPPs) accident, multi-unit probabilistic safety assessment (MUPSA) has significantly increased in the past few years. Human reliability analysis (HRA), which is generally performed as part of a PSA, has continued to take on increasing importance. Dependency between human failure events (HFEs) is often analyzed as a part of the conventional human reliability analysis (HRA) process for probabilistic safety assessment (PSA). To date, most of the dependency methods focused on the single-unit (SU) PSA model, such as the technique for human error rate prediction (THERP) [1], accident sequence evaluation program (ASEP) [2], Standardized plant analysis risk-HRA method (SPAR-H) [3], and Fire HRA method (NUREG-1921) [4].

However, most HRA methods are suitable for single-unit accident scenarios and may not be suitable for multi-unit (MU) accident scenarios [5]. The challenges of MU HRA may include the use of shared equipment between units, prioritization of equipment and personnel, additional organizations related to emergency response organizations (ERO), and delays in human actions due to radiation release from adjacent units. All these create additional interactions and sometimes unique dependencies between the HFEs in such scenarios.

In our previous efforts to address the issues of MU HFE dependency, the methodology for analyzing MU HFE dependencies was developed [6], and based on our practical experience from the Multi-Unit Risk Research Group (MURRG) project, a series of unique interactions of the HFEs were found [7].

Therefore, the purpose of this study is to propose a multi-dimensional approach to MU HFEs dependency analysis. Five unique characteristics were identified by analyzing the MU cutsets and the quantification result of MU PSAs. A description of the multi-dimensional analysis approach is described with two examples.

2. Identification of characteristics of multi-unit HFE dependency

2.1 Method

The MURRG conducted research to complete the development of a MU PSA model from 2017 to 2021 with the support of the Korean regulatory body. This MUPSA model includes internal and external initiating events, and at-power (AP) and low power-shutdown (LPSD) modes. In addition, the MU PSA model includes portable equipment in its analysis. The reference site includes nine units i.e., one Westinghouse 2-loop, 600 MWe reactor (WH600, termed U1), two Westinghouse 3-loop 900 MWe reactors (WH900, termed U2 and U3), two optimized power reactors (OPR1000, termed U4 and U5), and four advanced power reactors (APR1400, termed U6 to U9) [8,9].

To find the characteristics of MU dependency analysis, 818 MU cutsets including two or more HFEs were identified. These cutsets were selected based on their risk significance from the quantification results. As a result of the analysis, five unique characteristics of the MU cutset were found.

2.2 Characteristics of Dependency in the Multi-unit HFEs

1) Different operation modes.

A MU PSA cutset may include HFEs under different operation modes, which is impossible in a SU cutset. This characteristic was seen in 337 cutsets among 818 cutsets. The developed MU PSA model includes AP and LPSD operation modes. If the operation mode is different for each unit, there may be a difference in the accident scenario and the time to reach the core damage.

2) Two or more initiating events.

A MU PSA cutset can contain HFEs from two or more initiating events but this is not possible in a SU cutset. This characteristic accounts for 391 cutsets among 818 cutsets. When the initiating events between the units are different, the complexity of the ERO may increase.

3) Multiple preceding actions.

An HFE can be affected by multiple preceding actions. In the MU cutset, an HFE can be affected by multiple preceding actions, even by actions from other units. This characteristic was found in all MU cutsets containing 3 or more HFEs. The MU dependency analysis should consider all the possible interactions between the actions, which requires more effort than the SU analysis.

4) Emergency response organizations.

The MU dependency analysis should consider the involvement of EROs. This characteristic was found in 189 cutsets among 818 cutsets. ERO is established in the event of a MU accident. As shown in Figure 1, the ERO has organizations such as emergency operating facility (EOF), technical support center (TSC), operational support center (OSC), and sub-contractor.

In addition, the organization that conducts accident diagnosis is changed from the main control room (MCR) operators to TSCs. In Korea, one TSC is responsible per two units, which may increase the complexity of the TSC operation.

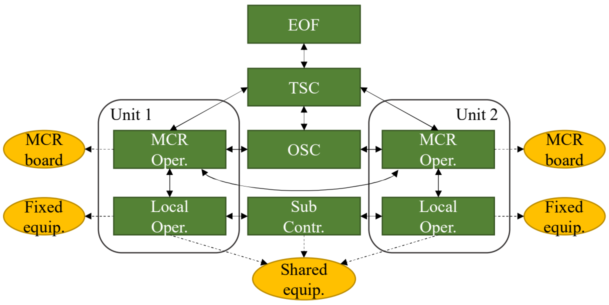

Fig. 1. ERO and equipment interaction in MU accident.

5) Limitation of shared resources.

The dependency analysis should consider the limitation of shared resources. This characteristic accounts for 4 cutsets among the 818 cutsets. In the MU scenario, some resources need to be shared. As seen in Figure 2, the resource can be systems such as mobile equipment and shared alternate diesel generators or man-power such as the personnel who transport and install the mobile equipment, TSC, OSC, or EOF.

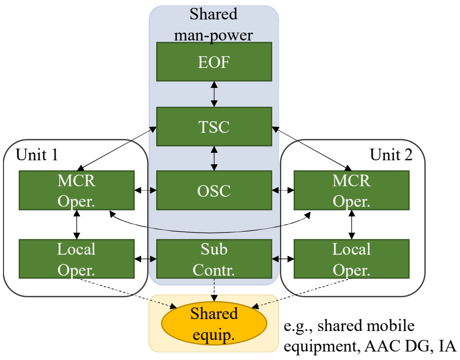

Fig. 2. Shared equipment and manpower between two units.

3. Multi-dimensional analysis for Multi-unit HRA dependency

A multi-dimensional analysis of the actual MU accident scenario is explained through an example. As described the section 2.2, multiple preceding actions may exist in MU cutsets. It is not known which preceding action has high dependencies before performing dependency analysis. Therefore, it is necessary to perform dependency analysis according to the following process.

1) Identify all possible interactions
2) Analyze dependency levels using the MU dependency method
3) Determine the higher dependencies among the interactions.

3.1 Example 1: Different Operation Modes, Same Initiating Event, Decision-making is Moved to ERO, and No Shared Resources in Twin-unit

Considering the example in Figure 3, U4 is in AP mode while U5 is in LPSD mode.

The U4 accident scenario is as follows. Before the initiating event, the maintenance personnel failed to restore the safety injection (SI) valve (U4-WOOPUHS-1049A). When the loss of offsite power (LOOP) event occurs, U4 is successfully tripped. However, one of the two emergency diesel generators (EDGs) fails to run, i.e., U4-EGDGR01B. As a result, the pressure in the primary loop increases due to an imbalance between the primary and secondary loops. A power-operated relief valve (PORV) automatically opens and closes to relieve the primary loop pressure. The steam generators are used to successfully remove the residual heat from the reactor coolant system (RCS). However, the operator failed to change the water source from the auxiliary feedwater storage tank (AFWST) to the condensate storage tank (CST). Then, the operator successfully opens the PORV for feed and bleed (F&B) operation, but the SI does not work due to an error in the maintenance crew (U4-WOOPUHS-1049A). So U4 tends towards core damage.

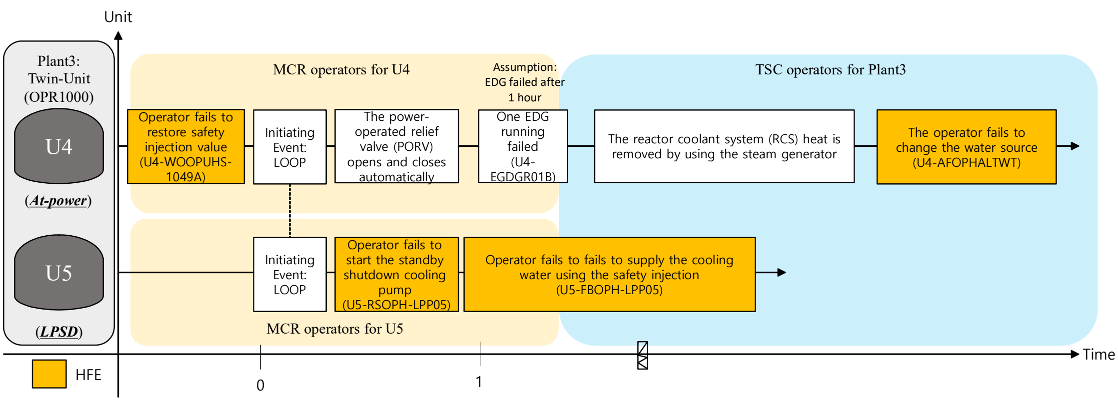

Fig. 3. MU scenario in example 1.

The U5 accident scenario is as follows. The U5 is under overhaul, i.e., LPSD. When the LOOP occurs, the shutdown cooling (SDC) pump is stopped. At this time, the operator manually starts the standby SDC pump, but it fails (U5-RSOPH-LPP05). Next, the operator fails to start safety injection (SI) pump to supply water (U5-FBOPH-LPP05). Consequently, the core undergoes damage.

The example on Figure 3 can be analyzed thus;
1) Identify all possible interactions

Three (3) interactions among the HFEs can be found i.e., 1) U5-HFE2 can be dependent on U5-HFE1, 2) U4-HFE1 can be dependent on U5-HFE1, and 3) U4-HFE1 can be dependent on U5-HFE2.

2) Analyze dependency levels using the MU dependency method

The dependency level of the various interactions was analyzed using the MU dependency method. As a result of analyzing the dependency level using the decision tree as shown in Figure 4, interaction one (1) was evaluated as low dependence (LD) using SU dependency method as in SPAR-H method [3], and interactions two and three (2 and 3) were evaluated as LD.

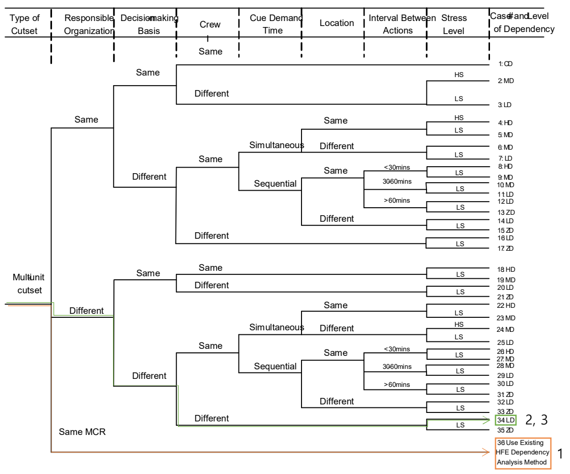

Fig. 4. 3 Dependency results of example 1.

3) Determine the higher dependencies among the interactions.

As seen in Figure 5, all three interactions were evaluated as LD. Among the three evaluation results, the dependency result of the interaction highlighted in red was used. In particular, U4-AFOPHALTWT can affect interaction 2 and 3. We determines which dependency result we used. Both interactions (2 and 3) have the same dependency level i.e., LD. Interaction 3 dependency is selected due to the event scenario time order.

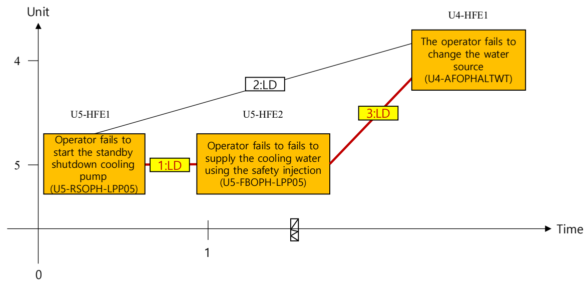

Fig. 5. Determined 2 dependency analysis results.

3.2 Example 2: Same Operation Mode, Same Initiating Event, Decision-making Move to ERO, and No Shared Resources in Twin-unit

Consider the example shown in Figure 6, the cutsets in U6 and U7 are identical. In the loss of condensate vacuum (LOCV) event, the reactors trip automatically and the residual heat is removed through the steam generators. However, the operators fail to perform the required SDC (U6-SCOPH-LTSDC-SCS and U7-SCOPH-LTSDC-SCS). Then, they also fail to change the water source to the steam generators (U6-AFOPH-AFWSC and U7-AFOPH-AFWSC). In addition, they fail to perform the F&B operation (U6-RCOPH-SDL-TR and U7-RCOPH-SDL-TR). Consequently, the series of HFEs will lead to core damage in the two reactors.

The example on Figure 6 can be analyzed thus;
1) Identify all possible interactions

Eleven (11) interactions among the HFEs can be found. This means U7-HFE1 can be dependent on U6-

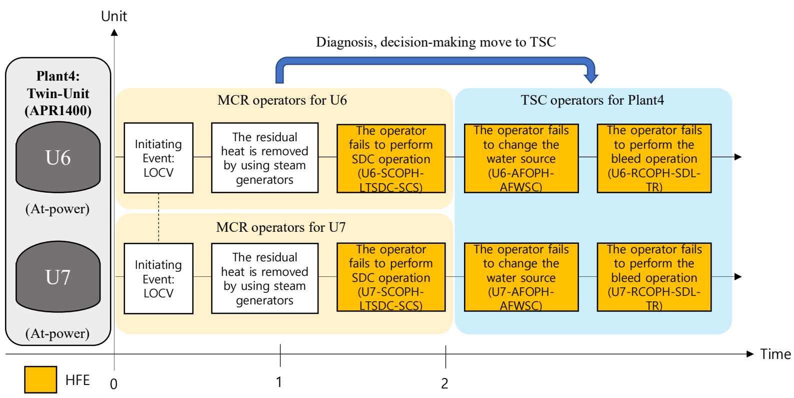

Fig. 6. MU scenario for example 2.

HFE1; U6-HFE2 can be dependent on U6-HFE1 and U7-HFE1; U7-HFE2 can be dependent on U6-HFE1, U7-HFE1, and U6-HFE2; U6-HFE3 can be dependent on U6-HFE2 and U7-HFE2; and finally, U7-HFE3 can be dependent on U6-HFE2, U7-HFE2, and U6-HFE3. Since the accident scenario of both units is the same, it is assumed that the time of occurrence for all the corresponding HFEs in both units is the same.

2) Analyze dependency levels using the MU dependency method.

Again, the dependency level of the various interactions was analyzed using the MU dependency method. As a result of analyzing the dependency level using the decision tree as shown in Figure 7, interactions one to nine (1~9) were evaluated as LD, and interactions ten and eleven were evaluated as moderate dependence (MD).

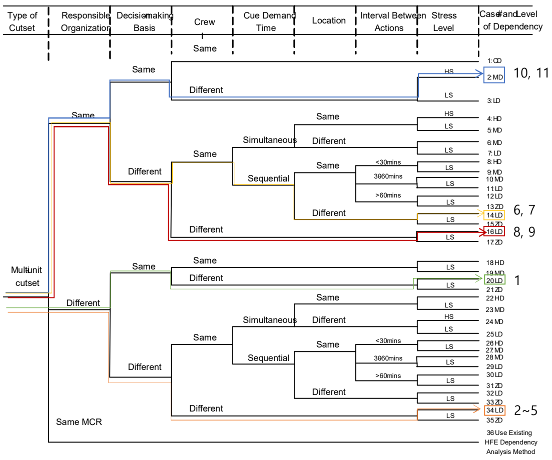

Fig. 7. Dependency results of example 2.

3) Determine the results of a high dependency analysis among analysis results

As shown in Figure 8, five interactions were determined. Among the eleven (11) evaluation results, the dependency result of the interaction highlighted in red was used. The result with the highest level of dependence was used. If results related to the target HFE were all at the same dependency level, it was assumed that the dependency within the same unit was higher.

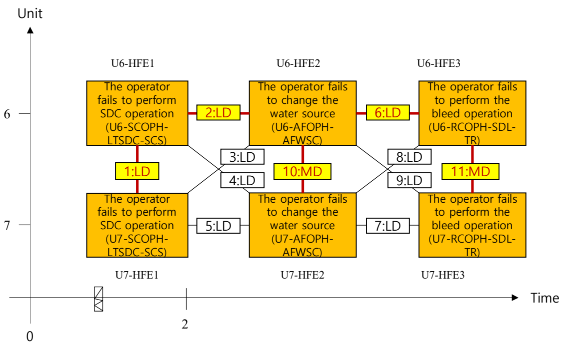

Fig. 8. Determined 5 dependency analysis results.

4. Conclusions

In this paper, the unique characteristics of HFs based on the MU cutsets have been described and a multi-dimensional approach to MU HFEs dependency analysis has been introduced. The multi-dimensional method is further described with two examples using real MU-PSA cutsets. Therefore, applying a conservative approach, it is possible to select a reasonable dependency result among various human interactions in MU scenarios.

Acknowledgments

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT). (No. RS-2022-00144172)

REFERENCES

[1] A. D. Swain and H. E. Guttmann, "Handbook of Human Reliability Analysis with Emphasis on Nuclear Power Plant Applications - Final Report," NRC, 1983, U.S. Washington.
[2] A. D. Swain, "Accident Sequence Evaluation Program Human Reliability Analysis Procedure," NRC, 1987, California.
[3] D. Gertman, H. Blackman, J. Marble, J. Byers, and C. Smith, "The SPAR-H Human Reliability Analysis Method," NRC, 2005, U.S.Washington.
[4] S. C. S. Lewis, "EPRI/NRC-RES Fire Human Reliability Analysis Guidelines," NRC, 2012, California.
[5] St Germain, S., Boring, R., Banaseanu, G., Akl, Y., & Chatri, H. (2017). Multi-unit considerations for human reliability analysis (No. INL/CON-17-41526). Idaho National Lab.(INL), Idaho Falls, ID (United States).
[6] A. M. Arigi, G. Park, and J. Kim. "Dependency analysis method for human failure events in multi-unit probabilistic safety assessments", Reliability Engineering and System Safety, vol. 203, (2020).
[7] G. Park et al. "Dependency Analysis of Human Failures in Multi-unit Scenarios: Types and Evaluation Method", Proceedings of the Probabilistic Safety Assessment and Management PSAM 16 Conference, June 26-July 1, 2022, Honolulu, Hawaii.
[8] K. Son et al. "Development of Level 1 Internal Event Single-unit PSA Models for Multi-unit Risk Profiles", 2021 International Topical Meeting on Probabilistic Safety Assessment and Analysis (PSA 2021), pp. 944–952, (2021).
[9] J. S. Kim et al. "Modeling portable equipment in probabilistic safety assessment of nuclear power plants", 2021 International Topical Meeting on Probabilistic Safety Assessment and Analysis (PSA 2021), pp. 592–600, (2021).