Development of Event Tree-Fault Tree Model and Mapping to a Bayesian Network Model for High-Wind PSA

Chaeyeon Go [a], Shinyoung Kwag [a*], Seunghyun Eem [b], Daegi Hahm [c]
[a] *Department of Civil & Environmental Engineering, Hanbat National University, 125 Dongseo-daero, Yuseong Gu, Daejeon, Republic of Korea*
[b] *Department of Convergence & Fusion System Engineering, Kyungpook National University, 2559, Gyeongsang-daero, Sangju-si, Gyeongsangbuk-do, Republic of Korea*
[c] *Structural and Seismic Safety Research Division, Korea Atomic Energy Research Institute, 989-111 Daedeok-daero, Yuseong Gu, Daejeon, Republic of Korea*
[*] *Corresponding author: skwag@hanbat.ac.kr*

Keywords : Probabilistic Safety assessment (PSA), High wind, Bayesian network (BN), Nuclear power plant (NPP), Conditional core damage probability (CCDP)

1. Introduction

High winds are among the major natural hazards that can trigger external events at nuclear power plants (NPPs) [1]. To quantitatively evaluate the impact of high winds on plant safety, a stepwise probabilistic safety assessment (PSA) framework is required: (1) hazard analysis to estimate the annual frequency for different wind-speed levels; (2) fragility analysis to evaluate structural and equipment capacity against specified wind speeds; (3) systems analysis using logical models such as event trees (ET) and fault trees (FT) to assess overall plant-system safety based on fragility-analysis results and random-failure data; and (4) convolution of these results to quantify the core damage (CD) frequency induced by high-wind events.

However, conventional ET-FT-based PSA has limitations in representing component dependencies, incorporating newly available observational data, and capturing complex multi-path interactions among events [2–3]. To address these limitations, this study employs a Bayesian network (BN) to perform a PSA for high-wind events. Specifically, this study focuses on developing a BN mapping from the ET-FT model for high wind and showing the model's probabilistic inference. In future studies, this model can be used to integrate causal relationships among wind hazards, handle correlated component fragility, and update system-level impacts in real time using observational data.

2. Methods and Results

The probabilistic hazard analysis aims to estimate the annual frequency of different wind speed levels. In this study, the wind speed return period data for the Busan region under the RCP 8.5 Future I scenario (2011–2040), reported by Hong et al. [4], were used. An extreme value distribution was fitted to the data to derive the wind hazard curve [5].

In the fragility analysis, structures and components that affect safe shutdown and accident mitigation functions were initially identified. Their wind fragility curves were evaluated using previous studies [6]. The random-failure data for the related equipment supporting the accident-mitigation function were adopted from the NPP's internal event PSA model. The probability data on the fragility curve and the random-failure for structures and components were then implemented into the BN model as probabilistic input nodes.

2.1 ET-FT High Wind Scenarios

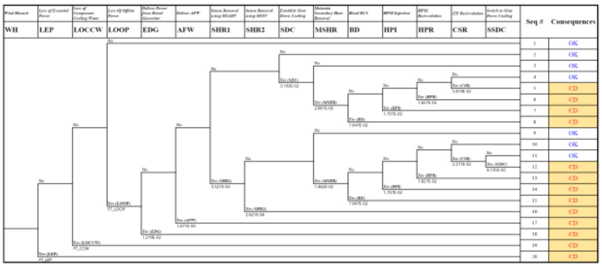

Fig. 1. ET for high-wind-induced accident scenarios

Figure 1 shows the developed high-wind PSA model, represented using an ET model. High-wind-induced accident scenarios that directly lead to core damage consist of three initiating events (IEs). First, loss of essential power (LEP) occurs when off-site power is lost and the 4.16 kV safety buses, including the emergency diesel generators (EDGs), also fail. Damage to the auxiliary or EDG buildings is conservatively assumed to result in the loss of all related safety power systems. Second, loss of component cooling water (LOCCW) refers to the failure of cooling functions due to structural damage to buildings housing the component cooling water (CCW) or essential service water (ESW) systems. Structural damage is conservatively assumed to cause complete system failure. Third, loss of off-site power (LOOP) is caused by wind-induced damage to vulnerable electrical equipment. If EDGs are unavailable, a station blackout (SBO) is assumed, which can lead to core damage. Aside from these three IEs, other IEs are constructed similarly to account for the safety features of the internal-event PSA ET modeling for the NPP.

2.2 Mapped BN Model

Figure 2 shows the BN model constructed by mapping from the one-top FT model, which was converted from the developed high-wind ET-FT PSA model. The CD is modeled as a child node at the bottom of the BN. The thirteen (13) consequences of the ET that result in the CD are modeled as child nodes in the layer directly above the CD node. The other IEs of the ET and the related basic components of the FT were modeled as child and parent nodes, respectively. The relations among nodes were represented as acyclic arrows, and their quantitative relationships were defined using conditional probability tables (CPTs). These arrows and CPTs were quantified to accurately reflect the relationships between the branches of the ET and the gates of the FTs.

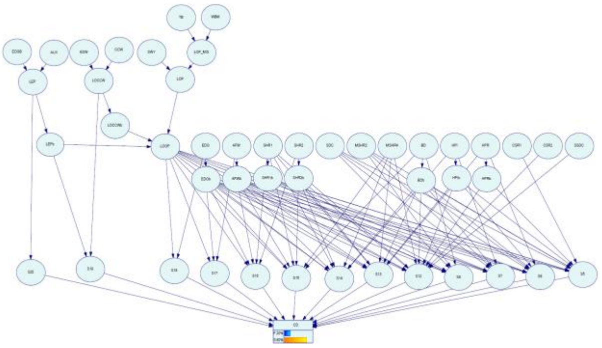

Fig. 2. Mapped BN model

2.3 Result

For the analysis of the ET-FT coupled model, the reconstructed one-top FT model was evaluated using the uni-modal bound (UMB) approach. Under the maximum wind speed condition of V_m = 60 m/s, the wind-induced conditional core damage probability (CCDP) calculated from the ET-FT model was 0.1942 (or 19.42%). For the same accident scenarios, probabilistic inference was performed using the BN model, yielding a CCDP value nearly identical to that obtained with the BN model. Consequently, the accuracy of the result was preserved even after mapping the ET-FT-based logical structure into a BN structure.

Furthermore, the impact of major component failures on overall risk was evaluated using the BN's probability inference. When the switchyard structure (SWY) was assumed to fail (failure probability = 1.0), the CCDP rose to 0.2134, an increase of approximately 4.2% from the baseline CCDP. In contrast, when the EDG was assumed to fail, the CCDP increased significantly to 0.3148, indicating that this component has a relatively greater influence on overall risk.

These results demonstrate that the BN-based approach enables direct inference of the overall CCDP under specified failure conditions at component or intermediate nodes. In other words, unlike the conventional ET-FT framework, which does not have an inference mechanism for such evaluations, the BN framework can ultimately enable real-time risk assessment and component importance evaluation.

3. Conclusions

In this study, the ET-FT model for high-wind PSA was mapped into a BN structure, and the analytical results of the two models were compared. The reconstructed one-top FT-based ET-FT model was evaluated using the UMB approach to quantify the CCDP, and probabilistic inference was performed with the mapped BN model for the same accident scenarios. The results confirmed that accuracy was maintained even after mapping the ET-FT-based logical structure into a BN structure under the base condition. Furthermore, the BN model's capability for conditional probability inference was used to quantitatively evaluate changes in overall CCDP under major component failure conditions. The analysis demonstrated that the overall CCDP can be directly inferred from specific component failure states, thereby enabling efficient assessments of component importance and sensitivity in future studies. The findings also suggest that the BN-based approach serves as a useful analytical tool to complement the conventional ET-FT-based PSA framework and has potential for future applications in real-time risk assessment and dynamic PSA model development.

ACKNOWLEDEMENT

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. RS-2022–00144328). Also, this work was supported by the Nuclear Safety Research Program through the Korea Foundation of Nuclear Safety (KoFONS), granted financial resources from the Nuclear Safety and Security Commission (NSSC), Republic of Korea (RS-2024-00404119).

REFERENCES

[1] S. M. Hess, S. Prescott, C. Smith, L. Lin, N. Dinh, R. Sampath, and N. Montanari, Integrated Use of Modeling and Simulation in High Winds PRA, Proceedings of the 2017 International Topical Meeting on Probabilistic Safety Assessment and Analysis (PSA 2017), American Nuclear Society, pp. 30-39, 2017.

[2] F. V. Jensen and T. D. Nielsen, Bayesian Networks and Decision Graphs, Springer, New York, 2007.

[3] N. Fenton and M. Neil, Risk Assessment and Decision Analysis with Bayesian Networks, Crc Press, 2018.

[4] S. M. Hong, W. S. Yoon, H. J. Ham, and W. H. Lee, Estimation of Future Basic Wind Speeds Based on RCP 8.5 Scenario, Journal of the Wind Engineering Institute of Korea, Vol.17, No.4, pp.133-139, 2013.

[5] A. M. Salman and Y. Li, Age-Dependent Fragility and Life-Cycle Cost Analysis of Wood and Steel Power Distribution Poles Subjected to Hurricanes, Structure and Infrastructure Engineering, Vol.12, No.8, pp.890-903, 2016.

[6] M. K. Ravindra, State-of-the-Art and Current Research Activities in Extreme Winds Relating to Design and Evaluation of Nuclear Power Plants, Geophysical Monograph Series, Vol.79, pp.389-397, 1993.