Transactions of the Korean Nuclear Society Autumn Meeting
Gyeongju, Korea, October 29-30, 2026

Development of a Time-Window Importance Measure in Dynamic PSA for Recovery Prioritization

Kyeongseo Kim, Seung Jun Lee*

Department of Nuclear Engineering, Ulsan National Institute of Science and Technology (UNIST)
**Corresponding author: sjlee420@unist.ac.kr*

***Keywords :** Dynamic PSA, Importance measure, Time-window RRW, MACST, Portable equipment*

1. Introduction

Probabilistic safety assessment (PSA) supports risk-informed decision making by quantifying the contributions of initiating events, systems, components, and human actions to plant risk. In conventional event-tree/fault-tree PSA, importance measures such as Fussell-Vesely (FV), risk achievement worth (RAW), risk reduction worth (RRW), and Birnbaum importance are evaluated from a baseline risk, R_0 and assumed risks obtained by assuming a basic event to be failed (R^+) or successful (R^-). These measures provide concise rankings of risk-significant contributors and are therefore useful for prioritization.

Dynamic PSA extends this framework by explicitly representing accident progression and the timing of stochastic events. Failure time, recovery time, and actuation delay can be continuous variables, so the binary perturbations used in static PSA do not by themselves indicate when a component is most important. Mandelli et al. derived conventional importance measures from simulation-based dynamic PSA data by estimating R_0, R^+, and R^- from sampled regions [1]. Xu et al. introduced time-dependent FV, RAW, and RRW by updating component probabilities according to state duration [2], while Narukawa et al. proposed timing-, frequency-, and consequence-based measures to reflect the multidimensional risk information generated by dynamic PSA [3]. These studies demonstrate the need for temporal importance information, but a direct conventional-importance conditioned on component start/run time windows remains useful for recovery-oriented decision support.

This issue is particularly relevant to post-Fukushima accident-mitigation strategies. Portable equipment used in Diverse and Flexible Coping Strategies (FLEX) and the Multi-Barrier Accident Coping Strategy (MACST), including mobile diesel generators and portable pumps, provides an additional defense layer when installed systems are unavailable. Because such equipment must be deployed, positioned, connected, and started before it can perform its safety function, its risk-reduction benefit depends strongly on the time at which it becomes available. Recent PSA studies have quantified the overall risk reduction from portable equipment and FLEX strategies [4,5], but an aggregate risk change does not directly identify which equipment should be recovered first or the latest time at which recovery still materially changes the accident outcome.

Accordingly, this study develops a time-window importance measure for dynamic PSA. The proposed approach partitions dynamic event times into discrete intervals, recalculates each scenario under forced failure and success conditions, and aggregates the resulting risks only over scenarios associated with the target time window. RRW is used as the primary measure because it directly represents the risk-reduction potential of successful recovery. The resulting time-window RRW is intended to quantify both recovery priority and the latest effective recovery time of MACST equipment during accident progression.

2. Method

2.1 Framework

Figure 1 shows the calculation framework developed to evaluate the time-dependent importance of basic events in Dynamic PSA. The framework consists of six sequential steps: (1) Dynamic PSA model construction, (2) time discretization, (3) calculation of basic-event probabilities in each time window, (4) calculation of top-event probabilities, (5) calculation and aggregation of assumed scenario risks, and (6) evaluation of time-window importance measures.

First, dynamic scenarios and the corresponding ET/FT models are defined. The accident progression is then divided into discrete time windows, and the probability of each basic event is evaluated according to its time interval relative to the target window. These probabilities are propagated through the fault-tree (FT) logic to obtain the top-event probability for each scenario and time

window. Subsequently, the baseline and assumed risks, R_0, R^+, and R^- are calculated for individual scenarios and aggregated over the scenarios belonging to each time window. Finally, conventional importance measures are evaluated separately for each time window to quantify how the risk significance of a basic event changes during accident progression.

2.2 Dynamic PSA Model Construction

The calculation begins with a dynamic PSA model consisting of an event tree (ET), FTs, and generated

dynamic scenarios. In contrast to static PSA, the Dynamic PSA scenarios contain assigned times of dynamic parameters such as component failure time, running time, recovery time, and delayed start-up time.

For each dynamic scenario, s, the values of the dynamic parameters determine when the corresponding top events occur during the accident progression. Therefore, scenarios having the same success/failure sequence may exhibit different risk characteristics when the associated event times are different. The proposed method preserves this temporal information and uses it as the basis for calculating scenario probabilities and importance measures within individual time windows.

2.3 Time Discretization

To quantify the effect of the timing, the accident progression is divided into a series of discrete time windows. Let the j-th time window be represented by $(t_{j-1}, t_j]$. The probability contribution associated with the basic event is determined according to the time assigned to that event in each scenario.

A left-bin rule is applied for the probability calculation. Under this rule, the time interval assigned to a component extends from the left boundary of the corresponding time window to the time assigned to the component. This approach allows continuous stochastic parameters, such as failure and delayed start-up times, to be consistently converted into probabilities associated with discrete accident-progression intervals. Consequently, each component state changes can be evaluated according to whether it occurred before, within, or after the target time window.

2.4 Probabilities in Each Time Window

For each basic event i in scenario s, the assigned time is classified relative to the target time window $T_k = (l_k, u_k]$. The three mutually exclusive states are defined as before (B), current (C), and after (A). The current state indicates that the event occurs within the target window; the before state indicates that it has already occurred by the left boundary l_k; and the after state indicates that it occurs later than the upper boundary u_k. The corresponding probabilities are

$$C_{i,k} = P(l_k < T_i \le u_k),\ B_{i,k} = P(T_i \le l_k)$$

$$A_{i,k} = P(T_i > u_k),\ B_{i,k} + C_{i,k} + A_{i,k} = 1$$

These state probabilities are obtained from the failure-time, running-time, recovery-time, or delayed start-up distribution assigned to the basic event. They are then propagated through the FT logic to determine the top-event probability associated with the same time window. For an OR gate, the top event is assigned to T_k when the earliest failure occurs in the current window; therefore, no event may have failed before l_k, and at least one event must fail in the current window. For N OR-gate event, this can be written as

$$P_{TOP,k}\,(OR) = \prod_{i=1}^{N}(C_{i,k} + A_{i,k}) - \prod_{i=1}^{N} A_{i,k}$$

For two basic events A and B, the admissible combinations are (A current, B after), (A after, B current), and (A current, B current). For an AND gate, the top event is assigned to T_k when the latest required event failure occurs in the current window. Thus, every required event must have failed no later than u_k, while at least one failure must occur in the current window:

$$P_{TOP,k}\,(AND) = \prod_{i=1}^{N}(B_{i,k} + C_{i,k}) - \prod_{i=1}^{N} B_{i,k}$$

For two basic events, the admissible combinations are (A current, B before), (A before, B current), and (A current, B current).

2.5 Assumed Risk per Scenario

After the time-window top-event probabilities have been evaluated, the occurrence probability of each dynamic scenario S is calculated from the top events that define the scenario. For a scenario containing m top events, the baseline scenario probability, which is used as the baseline risk contribution $R_{0,S}$ in the present core-damage scenario set, is

$$R_{0,s} = P_{Scenario,s} = \prod_{q=1}^{m} P_{TOP,q,s}$$

To quantify the importance of a target basic event e, the complete scenario probability is recalculated under two assumed conditions. R^+ represents the risk when the target basic event is forced to fail, whereas R^- represents the risk when it is forced to succeed.

For a static basic event, its fixed failure probability is set to 1 for R^+ and to 0 for R^-. For a dynamic event, the forced condition is applied to the time-dependent basic-event probability, and all affected top-event and scenario probabilities are recalculated. For a delayed start-up or recovery event, R^+ denotes that the equipment remains unavailable by the end of the selected time window,

Fig. 1. Calculation framework for the time-window importance measure.

while R^- denotes that the equipment is available at that time.

2.6 Time-window Importance Measures

The scenario-level risk quantities are aggregated only over scenarios assigned to the target time window. For basic event e and time window T_k, the scenario subset is defined as

$$S_{e,k} = \{s : t_e(s) \in T_k\}$$

The baseline and assumed risks are then summed over the same scenario subset so that the three quantities correspond to an identical time-conditioned set:

$$R_{0,e,k} = \sum_{s \in S_{e,k}} R_{0,s}, \quad R^+_{e,k} = \sum_{s \in S_{e,k}} R^+_{s,e}$$

$$R^-_{e,k} = \sum_{s \in S_{e,k}} R^-_{s,e} .$$

Conventional importance measures are subsequently calculated for each basic event/time-window using the aggregated risk quantities:

$$FV_{e,k} = \frac{R_{0,e,k} - R^-_{e,k}}{R_{0,e,k}}, \quad RAW_{e,k} = \frac{R^+_{e,k}}{R_{0,e,k}}$$

$$RRW_{e,k} = \frac{R_{0,e,k}}{R^-_{e,k}}, \quad Birnbaum_{e,k} = R^+_{e,k} - R^-_{e,k}$$

The time-window risk preserves the conventional definitions of FV, RAW, RRW, and Birnbaum importance while changing the risk over which R_0, R^+, and R^- are evaluated. Consequently, the importance of a component can be tracked as the accident progresses. In this study, RRW is used as the primary recovery-priority metric: a large RRW indicates a time window in which successful recovery of the component yields substantial risk reduction, whereas a decreasing RRW indicates diminishing benefit as the accident progresses.

3. Case study

The proposed time-window importance measure was applied to an OPR1000 model to demonstrate its capability for evaluating the time-dependent risk significance of accident mitigation and recovery actions. The initiating event considered in the case study was Loss of Offsite Power (LOOP). The accident progression following LOOP was represented using dynamic scenarios that account for the operating duration, start-up delay, and recovery time of mitigation systems.

Seven dynamic variables were considered: EDG running time, Alternative AC-Diesel Generator (AAC-DG) delayed start-up time, AAC-DG running time, offsite power recovery time, 3.2 MW Mobile Diesel Generator (MDG) delayed start-up time, Turbine Driven Pump (TDP) running time and Portable Low-pressure Pump (PLPP) delayed start-up time. The ranges and discretized values assigned to these variables are summarized in Table 1. The dynamic parameters were selected to represent both installed safety systems and recovery or portable mitigation equipment whose availability changes during accident progression. In particular, the 3.2 MW MDG and PLPP were included as MACST equipment whose delayed deployment can significantly affect accident mitigation.

Based on the discretized values of the seven dynamic variables, a total of 66,854,673 dynamic scenarios were generated and evaluated. Each scenario represents a distinct temporal combination of system operation, failure, delayed start-up, and recovery during the accident progression. The scenario information was subsequently used to calculate the scenario occurrence probabilities and the time-window importance measures according to the calculation framework described in Section 2.

The conditional core damage probability (CCDP) obtained from the conventional Static PSA model was 1.650×10^{-6}, whereas the CCDP calculated from the Dynamic PSA scenarios was 2.234×10^{-7}. Thus, the Dynamic PSA result was approximately 86.46% lower than the Static PSA result.

The difference indicates that consideration of the temporal relationships among component failures, operating durations, delayed start-up, and recovery can affect the estimated risk. While Static PSA represents system successes and failures primarily through fixed combinations, Dynamic PSA additionally accounts for whether a mitigation system becomes unavailable or is recovered at a time when its operation can still influence the accident progression. Therefore, the generated dynamic scenarios provide a basis for evaluating not only whether a system is important, but also when its availability becomes important.

Table I. Dynamic variables and discretization considered in the OPR1000 case study.

No.	Dynamic variable	Operating condition	Discretized values (hr)
1	EDG running time	After LOOP initiation	0, 4, 8, 12, 16, 20, 24, 28, 32, 36, 40, 44, 48, 52, 56, 60, 64, 68, 72 (19)
2	AAC-DG start delay time	After EDG failure	0.15, 1, 2 (3)
3	AAC-DG running time	After AAC-DG start-up delay	0, 4, 8, 12, 16, 20, 24, 28, 32, 36, 40, 44, 48, 52, 56, 60, 64, 68, 72 (19)
4	Offsite power recovery time	After LOOP initiation	0.5, 4, 8, 12, 16, 20, 24, 28, 32, 36, 40, 44, 48, 52, 56, 60, 64, 68, 72 (19)
5	3.2 MW MDG delayed start-up time	After AAC-DG failure	1.3, 4, 8, 12, 16, 20, 24, 28, 32, 36, 40, 44, 48, 52, 56, 60, 64, 68, 72 (19)
6	TDP running time	After EDG failure	0, 1, 2, 3, 4, 5, 6, 7, 8 (9)
7	PLPP start delay time	After AAC-DG failure	1.3, 4, 8, 12, 16, 20, 24, 28, 32, 36, 40, 44, 48, 52, 56, 60, 64, 68, 72 (19)

Using the Dynamic PSA scenario results, the time-window RRW was calculated for offsite power recovery, PLPP, and the 3.2 MW MDG, as shown in Fig. 2. The results demonstrate that the risk-reduction benefit of each recovery action varies considerably with the elapsed time after the initiating event. Among the three recovery actions, offsite power recovery exhibited the highest RRW over the overall accident progression. Its RRW was extremely high during the early time windows and decreased rapidly as recovery was delayed. This indicates that early restoration of offsite power provides

the largest potential reduction in core damage risk because it can restore electrical support to multiple mitigation functions.

When only the MACST equipment is considered, however, the recovery priority changes with time. During the 0–4 h time window, the PLPP shows the highest RRW, indicating that early availability of portable water injection capability provides the greatest risk-reduction benefit among the MACST equipment. From approximately 4 to 12 h, the 3.2 MW MDG becomes the most risk-significant MACST equipment, indicating an increasing dependence on portable AC power support after the initial accident response period. Therefore, the time-window RRW provides information that cannot be obtained directly from a single static importance value. The results identify not only the equipment having a large overall risk-reduction potential but also the time-dependent transition of recovery priority. For the present OPR1000 LOOP case, offsite power recovery remains the dominant recovery action overall, whereas the MACST recovery priority shifts from the PLPP during 0–4 h to the 3.2 MW MDG during 4–12 h.

4. Conclusion

This study developed a time-window importance measure for Dynamic PSA and demonstrated its application to an OPR1000 LOOP case. Seven dynamic variables describing component running time, start-up delay, and offsite power recovery were considered, resulting in 66,854,673 dynamic scenarios. The calculated CCDP decreased from 1.650×10^{-6} in Static PSA to 2.234×10^{-7} in Dynamic PSA, corresponding to an 86.46% reduction, showing that explicit treatment of event timing can substantially change the estimated accident risk. The time-window RRW further quantified how recovery priorities vary during accident progression. Offsite power recovery showed the highest overall risk-reduction significance. Among MACST equipment, PLPP was most important during 0–4 h, whereas the 3.2 MW MDG became dominant from 4–12 h. These results indicate that the proposed method can identify not only which recovery action is important, but also when its implementation is most effective, providing quantitative support for time-dependent recovery prioritization.

ACKNOWLEDGEMENT

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. RS-2022-00143695) and by the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Korea government (MOTIE) (No. RS-2024-00403194, Next-Generation Nuclear Technology Creation IP-R&D Talent (Human Resources) Development Project).

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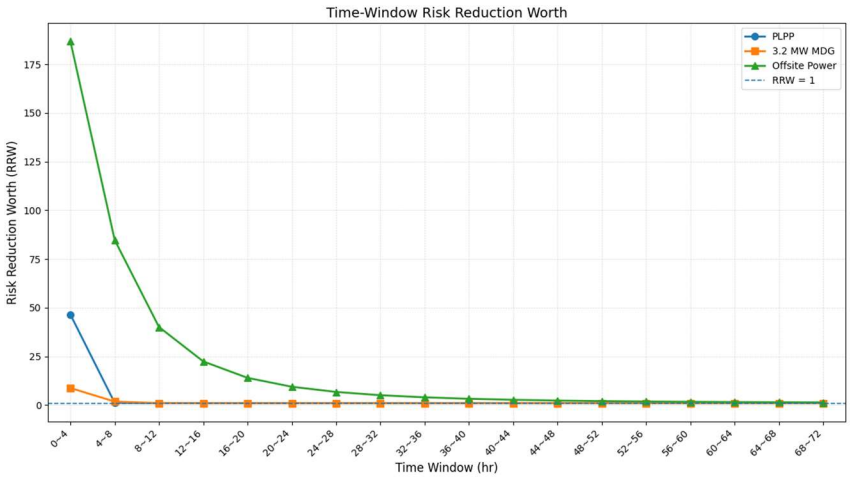

Fig. 2. Time-window risk reduction worth of offsite power recovery, PLPP, and 3.2 MW MDG.