

Risk Achievement-Based Screening of Human Failure Event Combinations for Fire HRA Dependency Analysis

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***Keywords :** Fire HRA, dependency analysis, HFE combination

1. Introduction

Dependency among Human Failure Events (HFEs) is an important consideration in Human Reliability Analysis (HRA), particularly in Fire Probabilistic Safety Assessment (Fire PSA), where multiple operator actions may occur within a single accident sequence. As Fire PSA models become increasingly detailed, the number of identified HFE combinations increases substantially, making detailed dependency evaluation of every combination impractical.

Industry guidelines, such as those by the Electric Power Research Institute (EPRI), suggest prioritizing HFE combinations prior to detailed dependency analysis using importance measures like Risk Achievement (RA), Dependency Importance (DI), and Fussell-Vesely (FV) [1–3]. Among these measures, RA was selected in this study as the initial screening metric because it can be evaluated before completing detailed dependency quantification. However, the EPRI process does not prescribe a quantitative threshold for determining how many RA-ranked combinations should be retained. Consequently, the extent of detailed dependency analysis may depend on analyst judgment.

This study proposes an RA-based screening procedure for identifying major HFE combinations requiring detailed dependency analysis. The proposed procedure ranks HFE combinations using an aggregated RA-based metric and determines the screening threshold objectively using the elbow-point method. The procedure was applied to a reference Fire PSA model to demonstrate its applicability.

2. RA-Based Screening Procedure

2.1 RA-Based Ranking Metric

Following the RA-based prioritization concept, the HEPs of all HFEs within the dependency-analysis scope were set to 1.0, and the Fire PSA model was quantified at the selected truncation level. Setting the relevant HEPs to 1.0 reflects the condition where all HFEs in a given combination are assumed to fail, thereby preventing their baseline HEP values from suppressing potential high-risk combinations during initial ranking.

An identical HFE combination may appear repeatedly in multiple quantified cutsets. Therefore, the integrated frequencies of all occurrences corresponding to the

same HFE combination were summed to obtain a single Aggregated Integrated Frequency (AIF) for each unique HFE combination. The resulting AIF represents the overall frequency associated with each unique HFE combination under the HEP = 1.0 condition and was used as the RA-based ranking metric. The unique HFE combinations were ranked in descending order of AIF.

2.2 Elbow-Point Screening Criterion

The elbow method is commonly used to identify a transition point in a ranked curve; however, identifying the elbow point by visual inspection may involve subjective judgment [4]. To provide an objective screening criterion, the elbow point was quantitatively determined using the maximum perpendicular-distance criterion. Each unique HFE combination was represented by coordinates $(r_i, \log_{10} AIF_i)$, where r_i denotes the rank of combination i . A logarithmic transformation was applied because the AIF values extended over several orders of magnitude. Without this transformation, the lower-ranked values would be compressed near the horizontal axis, making the overall ranking trend and its change in slope difficult to distinguish.

A reference line was constructed by connecting the first and last ranked points. The perpendicular distance from each ranked point to the reference line was calculated. The point with the largest distance was selected as the elbow point. This point indicates where the ranked AIF distribution deviates the most from the reference line. The elbow point was used as the cutoff for selecting HFE combinations for detailed dependency analysis. All combinations up to the elbow rank were selected. This cutoff was used only for screening and should not be interpreted as a formal risk-significance criterion.

Figure 1 summarizes the proposed screening procedure and Figure 2 presents the ranked AIF distribution of the reference Fire PSA model, together with the reference line connecting the first and last ranked points and the elbow point identified using the maximum perpendicular-distance criterion.

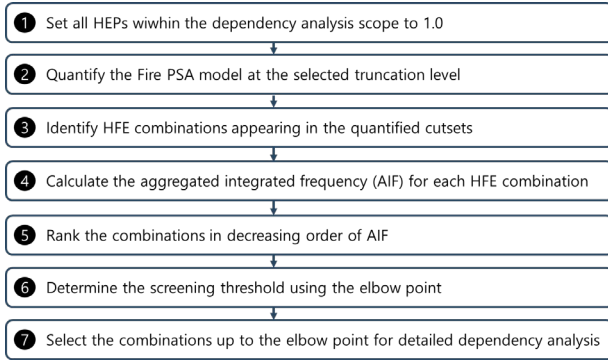


Fig. 1 Screening procedure of HFE combinations for dependency analysis

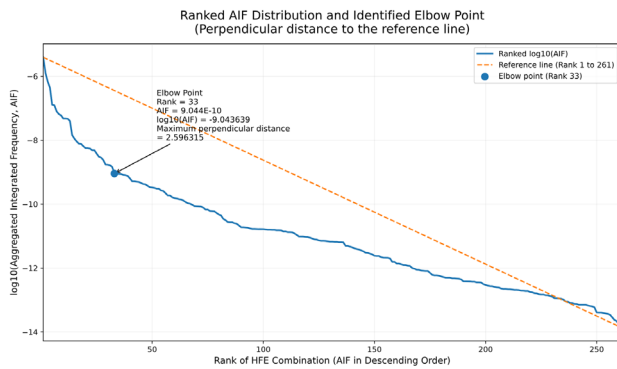


Fig. 2 Ranked AIF Distribution and Identified Elbow Point

3. Application and Results

The proposed procedure was applied to a reference Fire PSA model. After quantification with all HEPs within the dependency-analysis scope set to 1.0, identical HFE combinations appearing in multiple cutsets were consolidated. This process resulted in 261 unique HFE combinations.

An AIF value was calculated for each unique combination by summing the integrated frequencies of all corresponding occurrences. The 261 combinations were then ranked in descending order of AIF. As shown in Fig. 2, the AIF values span several orders of magnitude; therefore, the ranked distribution is presented on a base-10 logarithmic scale.

The reference line was defined by connecting the first and last points of the ranked $\log_{10}(AIF)$ distribution. The perpendicular distance from each ranked point to this line was calculated. The maximum perpendicular distance occurred at Rank 33, which was consequently identified as the elbow point and adopted as the screening threshold.

Based on this threshold, the first 33 HFE combinations were selected as candidates for subsequent detailed dependency analysis. The remaining combinations should not be interpreted as risk-negligible; rather, they fall below the screening

threshold established to prioritize the workload for detailed analysis.

The proposed procedure determines an objective screening cutoff. In particular, the method avoids selecting an arbitrary fixed number of combinations and instead determines the retained set from the shape of the ranked AIF distribution.

4. Conclusions

This study proposed an RA-based screening procedure for prioritizing HFE combinations before detailed dependency analysis in Fire HRA. The procedure uses the AIF, obtained by summing the integrated frequencies of all occurrences of the same HFE combination under the HEP = 1.0 condition, as the ranking metric.

To determine the extent of detailed analysis without adopting an arbitrary fixed rank or frequency cutoff, the elbow point method was applied to the ranked $\log_{10}(AIF)$ distribution. Application to a reference Fire PSA model identified 261 unique HFE combinations, and the maximum perpendicular-distance criterion identified Rank 33 as the screening threshold. Accordingly, the first 33 combinations were retained for subsequent detailed dependency analysis.

The proposed procedure provides a systematic and reproducible means of translating an RA-based ranking into a defined analysis scope. However, the elbow point serves only as a screening cutoff and does not represent a formal risk-significance criterion. Therefore, HFE combinations below the cutoff should not be interpreted as having no potential impact on the Fire PSA results.

Acknowledgment

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korean government, Ministry of Science and ICT. (Grant Code: RS-2022-00144204)

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