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Application of Jung's Method that Incorporates Human Failure Event Recovery into the Minimal Cut Set Generation Stage for APR 1400 PSA

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1. Introduction

Human reliability analysis (HRA) has been conducted to assess the impact of human errors on plant safety as part of the probabilistic safety assessment (PSA) that evaluates nuclear power plants safety [1,2]. PSA is a technical method used to evaluate the safety of NPPs and other complex systems. Through quantitative analysis, PSA assesses various events and potential risks that can occur within the system, predicting and evaluating their likelihood and consequences. The process of quantifying the PSA is depicted in Fig. 1. First, MCSs are generated by solving a fault tree [4,5]. Second, MCS recovery is performed to delete nonsense MCSs that have impossible failure combinations and to perform human failure event (HFE) recovery [6,7]. Third, the core damage frequency (CDF) is calculated by the min-cut-upper-bound (MCUB) from recovered MCSs [8]. Alternatively, an accurate CDF for seismic PSA is calculated by converting MCSs into a binary decision diagram (BDD) [8].

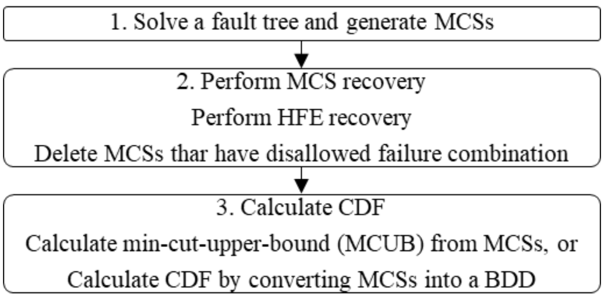

Fig. 1. PSA procedure [3]

Currently, there are three types of dependencies in PSA. First, there is an HFE dependency that uses the Recovery rule. Second, there is an internal event dependency using common cause failure (CCF). Finally, there is a seismic PSA that uses integration. This paper will address HFE dependency. For efficient HFE dependency analysis, it is necessary to generate as many minimal cut sets (MCSs) with HFE combinations in fault tree as possible after collecting potential HFE combinations. Then, in each MCS, it analyzes the level of dependency of the subsequent HFE on the preceding HFE and assign it as a conditional probability. After analyzing and assigning probabilities, HFE recovery is performed to re-enforce these conditional probabilities in MCSs by modifying MCSs [3]. Inaccurate HFE dependency analysis and HFE recovery could result in the truncation of MCSs, including HFE combinations. This can lead to an underestimation of CDF. Because of these issues, Jung's method [3] was proposed. This method incorporates HFE recovery into the MCS generation stage. This method can (1) reduce the total time and burden for MCS generation and HFE recovery, (2) prevent the truncation of MCSs that have dependent HFEs, and (3) avoid CDF underestimation. This method is simple but very effective tool of performing MCS generation and HFE recovery simultaneously and improving CDF accuracy. In this paper, Jung's method for validation applied to an APR 1400 PSA and compare with typical method.

Jung's method can be performed through the Z_METHOD [9] option in fault tree reliability evaluation expert (FTREX) [4-6,9]. To establish effective HFE recovery rules, it is necessary to identify as many HFE combinations as possible in the PSA model. To collect as many HFE combinations as possible in actual PSA model, (1) huge MCSs are generated by using low truncation limit or intentionally increasing HFE probabilities, (2) HFE combination probabilities in MCSs are adjusted by HRA, and (3) these combinations and their adjusted probabilities are written into cutset recovery file. Then, whenever MCSs are generated, HFE combinations and their probabilities in in MCSs are processed by this cutset recovery file [9]. However, it's important to note that many cut sets with HFE combinations in the cut set recovery file are often truncated during the cut set generation stage before applying cut set post-processing. The purpose of human failure event functions in FTREX (/Z_METHOD=[0|X|1|2]) is to (1) provide HFE combinations as many as possible with or without lowering the truncation limit, (2) give opportunity to modify cutset recovery rule to reflect probabilities of these HFE combinations into cutsets, and (3) apply recovery rules to these cutsets. The functions below will drastically reduce HRA burden for testing and generating HFE combination probabilities. These functions can be used for EPRI HRA Calculator or similar tools. Information related to these functions will be further elaborated in Section 3.

HFE dependency analysis is described in Section 2. HFE quantification method and application to APR 1400 is described in Section 3. The conclusion is in Section 4.

2. HFE dependency analysis

2.1 Typical HFE dependency analysis

HFE dependency analysis aims to determine the level of dependency of each combination of HFEs, which is determined using a process that considers various human factors and performance impact factors of the HFEs. MCS is a minimal combination of initiating events, component failures, and HFEs that leads to core damage of NPP. The HFEs in a single MCS could be arranged chronologically according to the corresponding incident sequence. These are used to analyze the dependency level of subsequent HFEs on preceding HFEs in each MCS and to determine human error probabilities (HEPs) for HFE recovery. The analysis procedure for HFE dependency analysis is depicted in Fig. 2. In a typical method, the dependent HEP of the subsequent HFE was calculated by Table 1 [2]. HFE dependencies were determined according to the dependency decision tree.

Table 1. HFE dependency level [2]

P(HFE-FNB-DP) = P(HFE-FNB)	for zero dependency
P(HFE-FNB-DP) = (1+19*P(HFE-FNB))/20	for low dependency
P(HFE-FNB-DP) = (1+6*P(HFE-FNB))/7	for medium dependency
P(HFE-FNB-DP) = (1+P(HFE-FNB))/2	for high dependency
P(HFE-FNB-DP) = 1	for complete dependency

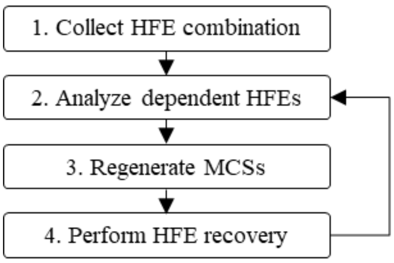

Fig. 2. HFE dependency analysis [3]

HFE dependency analysis consisted of four activities: (1) collect HFE combinations, (2) analyze dependent HFEs to determine dependency levels between subsequent and preceding HFEs, (3) regenerate MCSs, and (4) perform HFE recovery. In this paper, HFE recovery is defined as post-processing MCSs to reflect the dependent probabilities of HFEs within MCS probabilities [3]. In PSA, HFEs usually have positive dependency on their preceding HFEs. It was widely acknowledged that neglecting this positive HFE dependency could lead to an underestimation of the CDF. On the other hand, assuming complete HFE dependency would lead to an underestimation of the CDF.

2.2 Issues in typical HFE dependency analysis

The issues of HFE dependency analysis in Fig. 2 are summarized as follows [3]:

1. Issues in collecting HFE combinations: HFE combinations can be collected by assigning a very high HEP (0.9 or 1.0) to all HFEs, by lowering the cutoff limit as much as possible, or by a combination of the two. In each of these cases, it takes long time to solve the fault tree and generate the MCS.
2. Issues in analyzing dependent HFEs: The number of HFE combinations in the calculated MCSs sometimes exceeds 10,000, and the number of HFE combinations in a single MCS in a typical PSA varies from 1 to 10. Due to the large number of HFE combinations, analyzing the dependency of subsequent HFEs on the preceding HFEs is a very complex task.
3. Issues in regenerating MCSs: After applying the dependency level of the preceding HFE to subsequent HFEs, MCSs with HFEs remaining above the dependency level need to be recalculated with a higher HEP to avoid being cut by the truncation limit, which takes long time.
4. Issues in performing HFE recovery: HFE post-processing is performed repeatedly at each time when the MCS is recalculated. HFE post-processing often takes longer than computing the MCS.

Jung’s method can address the issues 3 and 4 by integrating HFE recovery into the MCS generation stage. Typical HFE dependency analysis has the following limitations: (1) there is no guarantee that all possible HFE combinations have been identified for the truncation limit chosen during quantification, and (2) the quantification process must be repeated for HFE dependency analysis, which makes the process complex and time-consuming. These limitations lead to an imprecise analysis of HFE dependency and subsequent recovery (refer to section 2.3), ultimately resulting in an underestimation of the CDF.

2.3 Perform HFE recovery

Once the dependency levels among HFEs are determined, a dependent HFE in a single MCS needs to be replaced with a new HFE with a dependent HEPs, or a new HFE with a joint probability of a combination of HFEs. This process is typically facilitated through dedicated tools [3,6]. As shown in Eqs. (1) and (2), the first step in performing an HFE recovery is as below. First, replace dependent HFEs ($H2$ and $H3$) with new HFEs ($H2'$ and $H3'$) that have conditional probabilities in Eq. (3) or to replace the whole HFE combination ($H1H2H3$) with a single HFE ($H123$) that has the product of conditional probabilities in Eq. (4) [3].

$$H1H2H3 \rightarrow H1H2'H3' \quad (1)$$

$$H1H2H3 \rightarrow H123 \quad (2)$$

where

$$\begin{aligned} p(H2') &= p(H2|H1) and\ p(H3') \\ &= p(H3|H1H2) \approx (H3|H2) \end{aligned} \quad (3)$$

$$\begin{aligned} p(H123) &= p(H1)p(H2|H1)p(H3|H1H2) \\ &\approx p(H1)P(H2|H1)p(H3|H2) \end{aligned} \quad (4)$$

To avoid underestimating the CDF, unanalyzed HFE combinations are treated conservatively. If some of the HFEs match the combination (H1H2H3), the probability of HFEs not included in the combination (H4H5) is set to 1.0.

$$H1H2H3H4H5 \rightarrow H1H2H3 * H4H5 \quad (5)$$

$$p(H4) = p(H5) = 1 \quad (6)$$

If no combination is matched, the first HFE has its nominal HEP, and the others are set to 1.0. This example is shown in Eq. (7).

$$\begin{aligned} &H1H4H5 \text{where} p(H1) < 1 \\ &\text{and } p(H4) = p(H5) = 1 \end{aligned} \quad (7)$$

3. Jung's HFE quantification method

3.1 Jung's method to incorporate HFE recovery into MCS generation stage

Jung's HFE quantification method [3] focuses on (1) collecting a maximum number of HFE combinations without lowering the MCS truncation limit and (2) performing MCS generation and HFE post-processing simultaneously. Fig. 3 describes the procedure of Jung's method.

Jung's method has been integrated into the FTREX [4-6,9]. A detailed example of applying this method to a basic fault tree is provided in Appendix A. Fig. 4 describes a relation between Jung's method and typical method.

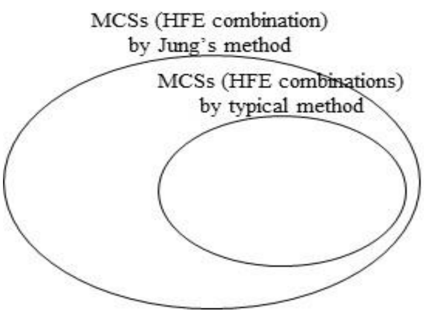

Fig. 4. Relationship between MCSs generated by Jung's method and typical method

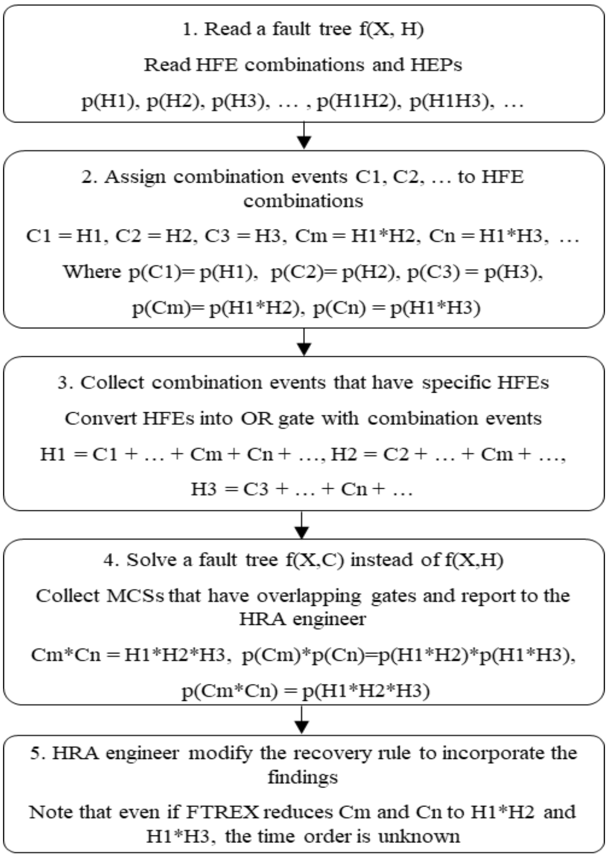

Fig. 3. Procedure of Jung's HFE method

Eq. (8) presents the results of the delete-term approximation (DTA) [8] between Jung's method and the typical method. When applying the delete-term approximation to Jung's method for eliminating MCSs generated through the typical approach, only additional MCSs remained. In the opposite case, no MCSs were remain. This substantiates that Jung's method consistently generates a higher number of MCSs compared to the typical method under the same truncation limit. Moreover, it indicates that MCSs remain untruncated when employing this method.

$$Delterm(MCS_J, MCS_T) \neq \emptyset \quad (8)$$
$$Delterm(MCS_T, MCS_J) = \emptyset \quad (9)$$

Here, MCS_J and MCS_T are MCSs by Jung's method and typical method, respectively.

3.2 Application of Jung's method to APR 1400 PSA

Jung's method can be applied to APR 1400 PSA model by FTREX [4-6,9]. This method is implemented through the human failure event function with the command (/Z_METHOD=3) [9]. By using human failure event function(/Z_METHOD=3) and /Z_FILE_INP=HFE.txt, /RULE=REC.txt, FTREX generates MCSs that have HFE combinations in HFE.txt as many as possible without lowering down truncation limit, and then apply recovery rules to the survived cutsets. HFE.txt has HFE combinations and their adjusted probabilities. A more detailed explanation of this function is presented in Table 2.

Table 2. Human failure event functions (FTREX)

/Z_METHOD =[0|X|1|2|3]	Set method for extracting HFE combinations (default=0) X Truncate MCSs with max(P1,X)*max(P2,X)*… 1 Truncate MCSs with mul(P1,P2,P3) 2 Truncate MCSs with max(P1,P2,P3) 3 Calculate MCSs quickly with HFE combinations in /Z_FILE_INP=[FILE] If /RULE=[FILE], cutsets under truncation limit are input to cutset recovery If no /RULE=[FILE], cutsets under truncation limit are written to output file
/Z_FILE_INP =[FILE]	Read HFE events and HFE combinations from the file FILE has HFE events for /Z_METHOD=1 or 2 0.2 H1 0.3 H2 or FILE has HFE events and HFE combinations /Z_METHOD=3 0.2 H1 0.3 H2 0.1 H1 H2
/Z_FILE_OUT =[FILE]	Write HFE combinations in MCSs at the file

When applying this method to PSA model, recovery rules need to be defined. This allows the incorporation of HFE recovery into the MCS generation stage. The HFE recovery rule contains the probabilities of HFEs and the HFE combinations for which dependencies have been completed. Table 3 shows the fault tree of the APR 1400 model, including the number of gates, number of events, etc. Table 4 and 5 show the details of the recovery rule that includes probabilities of HFEs and HFE combinations. Additionally, other recovery rules that do not include HFEs remain unchanged. The names and probabilities of HFEs are based on APR 1400 PSA.

Table 3. APR 1400 model fault tree

Gate	13,811
Event	4,499
-Gate	237
-Event	0
Event ($P = 1$)	237
Initiating event	19

Table 4. HFEs in APR 1400 model

HFE	Probability
H01	0.1
H02	6.36E-04
H03	6.36E-04
H04	5.77E-04
H05	1.39E-03
H06	2.14E-02
H07	1.47E-03
H08	7.85E-03
…	
H27	7.71E-3
H28	7.71E-3

Table 5. HFE combinations in recovery file

HFE combination				Probability
01	H07	H01		2.11E-04
02	H04	H01		2.12E-04
03	H07	H04		2.53E-04
04	H02	H03		5.06E-03
05	H07	H02		5.77E-04
06	H03	H03		6.36E-04
…				
27	H01	H03	H02	5.06E-03
28	H02	H04	H03	5.77E-04

This allows for the incorporation of HFE recovery into the MCS generation stage and the implementation of recovery rules that do not include an HFE combination. The changes in fault trees, MCSs, and CDF can be observed through the application of Jung's method to APR 1400 PSA. The results of PSA quantification using Jung's method and typical methods are shown in Table 6 and 6. The PSA quantification process was conducted using FTREX.

Fig. 4 depicts the correlation between Jung's approach and the typical method. The additional MCSs generated by Jung's method do not overlap with those from the typical method, which has already been validated through Eq. (8). Table 8 provides a comparison between the outcomes of Table 6 and Table 7. This table illustrates the difference achieved by subtracting the MCSs generated using Jung's method from those produced by the typical method. Given our prior confirmation that the generated MCSs are distinct (as outlined in section 3.1), this subtraction can be carried out straightforwardly. Due to the extremely small value of CDF, it has been converted and presented as a percentage.

Table 6. Results by typical method

Truncation limit	Calculation time (sec)	Number of MCSs	CDF
1.0E-09	1.58	152	7.356E-07
1.0E-10	2.36	1,165	1.139E-06
1.0E-11	2.48	5,398	1.264E-06
1.0E-12	4.25	24,022	1.335E-06
1.0E-13	9.20	95,117	1.364E-06
1.0E-14	23.23	356,508	1.376E-06
1.0E-15	64.10	1,287,943	1.398E-06

Table 7. Results by Jung's method

Truncation limit	Calculation time (sec)	Number of MCSs	CDF
1.0E-09	1.56	166	8.566E-07
1.0E-10	2.08	1,212	1.181E-06
1.0E-11	2.71	5,699	1.313E-06
1.0E-12	4.40	25,328	1.376E-06
1.0E-13	9.33	100,052	1.394E-06
1.0E-14	26.90	374,350	1.402E-06
1.0E-15	67.84	1,357,756	1.405E-06

Table 8. Comparison of Jung's method and typical method

Truncation limit	MCSs by Eq. (8)	MCSs by Eq. (9)	ΔCDF (a)
1.0E-09	14	0	16.45%
1.0E-10	47	0	3.69%
1.0E-11	301	0	3.84%
1.0E-12	1,306	0	2.70%
1.0E-13	4,935	0	2.13%
1.0E-14	17,842	0	1.88%
1.0E-15	69,813	0	0.47%

(a) $\frac{CDF(MCS_J) - CDF(MCS_T)}{CDF(MCS_T)} * 100(\%)$

Table 7 demonstrates that Jung's method consistently generates more MCSs compared with the typical method. Because it discovers a greater number of MCSs, it also demonstrates an increased CDF. When using this method, regardless of the truncation limit, the overall count of MCSs has increased. The reason for the reduction in the difference of CDF as the truncation limit decreases is that MCSs that contribute to raising the CDF have already been discovered. Usually, in the quantification process of PSA, the truncation limit falls within the range of 1.0E-12 to 1.0E-13, thus rendering Jung's method highly effective.

3.3 MCSs that require additional HFE dependency analysis

In the current domestic PSA, recovery rules are formulated through dependency analysis for a maximum of three combinations of HFEs. However, Jung's method identified MCSs comprising up to three HFE combinations and revealed HFE combinations where the dependency analysis was incomplete. By employing a truncation limit of 1.0E-10, a total of nine HFE combinations were identified that required the inclusion of recovery rules, as detailed in Table 9. For HFE combinations in Table 9, additional dependency analysis work by HRA experts is required, which will allow for a more accurate PSA. By re-quantifying to consider the analyzed dependencies, more HFE combinations can be identified. Through iterative execution of this procedure, more precise PSA results can be achieved.

Table 9. HFE combinations requiring additional HFE dependency analysis (1.0E-10)

HFE combination		
H04	H14	
H04	H29	
H10	H21	
H15	H30	
H15	H30	H31
H15	H11	H30
H15	H31	H03
H15	H22	H30
H30	H10	H22

4.Conclusions

In the previous sections of this paper, the advantages of Jung's method have been demonstrated. This method (1) reduces the overall time and effort associated with MCS generation and HFE post-processing, (2) avoids underestimating the CDF by not truncating MCSs with dependent HFEs, (3) identifies HFE combinations with incomplete dependency assessments, allowing for further dependency analysis, and (4) can be implemented in various PSA tools, as it was in the fault tree solver (FTREX) [4-6,9]. Given the current HFE dependency analysis, uncertainties arise concerning the comprehensive generation of all potential HFE combinations and the accurate recovery of dependencies between HFEs. Furthermore, the process of generating numerous MCSs with heightened HEP, conducting HFE dependency analysis, and subsequently implementing recovery rules consumes a substantial amount of time. Hence, there has been a pressing necessity for a method to alleviate the burden associated with HFE recovery. This method achieves this by integrating HFE recovery into the MCS generation stage. While this method may be simple in design, its concurrent execution of MCS generation and HFE recovery proves remarkably effective, ultimately enhancing the precision of CDF estimation. It is recommended that this method be embraced across various PSA contexts and applications, including risk monitoring, to facilitate swift and accurate CDF calculations. Moreover, its potential implementation spans diverse PSA tools, as demonstrated by its successful integration into the FTREX.

Acknowledgement

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REFERENCES

[1] M. Cepin, DEPEND-HRA-a method for consideration of dependency in human reliability analysis, Reliab. Eng. Syst. Saf. 9, 1452-1460, 2008.
[2] NUREG/CR-1278, Handbook of Human Reliability Analysis with Emphasis on Nuclear Power Plant Applications, 1983.
[3] W.S. Jung, How to incorporate human failure event recovery into minimal cut set generation stage for efficient probabilistic safety assessments of nuclear power plants, Reliab. Eng. Syst. Saf. 54, 110-116, 2022.
[4] W.S. Jung, S.H. Han, J.J. Ha, A fast BDD algorithm for the reliability analysis of large coherent systems, Reliab. Eng. Syst. Saf. 83 (3), 369-374, 2004.
[5] W.S. Jung, S.H. Han, J.J. Ha, An overview of the fault tree solver FTREX, in 13th International Conference on Nuclear Engineering, Beijing, China, May 16-20, 2005.
[6] W.S. Jung, ZBDD algorithm features for an efficient probabilistic safety assessment, Nucl. Eng. Des. 239 (10) 2085-2092, 2009.
[7] C.L. Smith, R.D. Fowler, SAPHIRE 'Recover Cut Sets' editor: a technique for automating the manipulation of PRA cut sets, Reliab. Eng. Syst. Saf. 54, 47-52, 1996.
[8] W.S. Jung, A method to improve cutset probability calculation in probabilistic safety assessment of nuclear power plants, Reliab. Eng. Syst. Saf. 134, 134-142, 2015.
[9] FTREX 2.0 User Manual, EPRI, Palo Alto, CA and KAERI, Daejeon, South Korea: 3002018234. 2020

APPENDIX A. Example of Jung's method [3]

Jung's method has been implemented into the fault tree reliability evaluation expert (FTREX) [4-6]. FTREX generates a new fault tree $f(X, C)$ by combining a given fault tree $f(X, H)$ and HFE combinations and generates MCSs without employing HFE recovery using Jung's method. This method with a fault tree is explained with an example in Eq. (A.1) [3]:

$$\begin{aligned} CD &= G1 + G2 + G3 \\ G1 &= A * (B + H1) \\ G2 &= B * (C + H2) \\ G3 &= C * D * H1 * H2 \end{aligned} \quad \text{(A.1)}$$

(Step 1) The results of the HFE dependency analysis, such as the joint HEP, such as $p(H1 * H2)$ in Eq. (A.2), are input to this procedure. FTREX reads the HFE combinations and their corresponding probabilities from Eq. (A.2). The combined probability, $p(H1H2)$, is much higher than $p(H1) * p(H2)$.

$$\begin{aligned} p(H1) &= 0.001 \\ p(H2) &= 0.001 \\ p(H1 * H2) &= 0.005 \end{aligned} \quad \text{(A.2)}$$

(Step 2) FTREX assigns combination events $C1 - C3$ to HFE combinations in Eq. (A.3).

$$\begin{aligned} C1 &= H2, p(C1) = 0.001 \\ C2 &= H2, p(C2) = 0.001 \\ C3 &= H1 * H2, p(C3) = 0.005 \end{aligned} \quad \text{(A.3)}$$

(Step 3) The special mapping between combination events $C1 - C3$ and HFE combinations is depicted in Eq. (A.3). H1 is in combination events $C1$ and $C3$, and $H2$ is in combination events $C2$ and $C3$. Using this mapping information, FTREX converts the $H1$ and $H2$ events into logical OR gates in Eq. (A.4).

$$\begin{aligned} H1 &= C1 + C3 \\ H2 &= C2 + C3 \end{aligned} \quad \text{(A.4)}$$

(Step 4) FTREX combines the given fault tree in Eq. (A.1) with the mapping information in Eq. (A.4) to solve the new fault tree in Eq. (A.5). Note that $H1$ and $H2$ are not events, but rather logical OR gates that combine events $C1 - C3$.

$$\begin{aligned} CD &= G1 + G2 + G3 \\ G1 &= A * (B + H1) \\ G2 &= B * (C + H2) \\ G3 &= C * D * H1 * H2 \\ H1 &= C1 + C3 \\ H2 &= C2 + C3 \end{aligned} \quad \text{(A.5)}$$

where

$$\begin{aligned} p(C1) &= 0.001 \\ p(C2) &= 0.001 \\ p(C3) &= 0.005 \end{aligned} \quad \text{(A.6)}$$

The MCSs computed from the fault tree in Eq. (A.5) is in Eq. (A.7). It is important to note that the dependency between H1 and H2 is inherently affected in Eq. (A.7) by using the combination event $C3$ by assigning $p(C3) = p(H1 * H2)$ in Eq. (A.3). The joint HEP of $p(H1 * H2)$ is the input to this procedure. Without Jung's method, the MCSs with $H1 * H2$ can be truncated to a given truncation limit. However, the MCSs with $C3$ cannot be truncated to the same truncation limit because $p(C3)$ is larger than $p(H1) * p(H2)$. Therefore, in this method, there is no need to increase the probabilities of $H1$ and $H2$. This saves computational time to generate MCSs and perform HFE recovery, which is a huge benefit.

$$\begin{aligned} CD \\ &= A * B + B * C + A * (C1 + C3) + \\ &\quad C * (C2 + C3) + C * D * (C3 + \\ &\quad C1 + C2) \end{aligned} \quad \text{(A.7)}$$

Many HFE combinations, such as H1H2, are truncated in a typical PSA with a given truncation limit. However, as shown in Eq. (A.7), all the intended HFE combinations {H1, H2, H1H2} are generated using the combination events $C1, C2, C3$. Multiple combination events in each MCS, such as $C1 * C2$ in Eq. (A.8), can be selectively created or deleted during MCSs generation using a dedicated PSA tool. If the PSA engineer is confident that all HFE combinations have been found and that the joint probabilities of those combinations have been appropriately assigned based on the truncation limit, there is no need to generate multiple combination events. On the other hand, these multiple combination events can be optionally generated to check if any HFE combinations are missing from Eq. (A.2). This is one of the main strengths of Jung's method.

$$
\begin{aligned}
CD &= A*B + B*C + A*(C1 + C3) + B*(C2 + C3) + C*D*(C3 + C1*C2) \\
&= A*B + B*C + A*(H1 + H1*H2) + B*(H2 + H1*H2) + C*D*H1*H2
\end{aligned}
\quad (A.8)
$$

The above process results in $C1$, $C2$, and $C3$ being visible in the MCS, and if HFE recovery is not perfect, $C1$ and $C2$ can exist simultaneously in one MCS. Since $C1$ and $C2$ can be created simultaneously in one MCS, the following measures are required to prevent this.

1. As shown above, it reports the MCSs where $C1$ and $C2$ exist at the same time, and the HRA engineer needs to analyze and modify the HRA post-processing.
2. Even if FTREX converts $C1$ and $C2$ back to HFEs, it is difficult to distinguish between leading and trailing HFEs (because the trailing HFEs do not know which HFE have not been renamed), so additional analysis by HRA engineers is required.
3. The quantification process should be repeated to perfect the HFE recovery rule.