Nuclear Engineering and Technology xxx (xxxx) xxx

Contents lists available at ScienceDirect

Nuclear Engineering and Technology

journal homepage: www.elsevier.com/locate/net

Direct fault-tree modeling of human failure event dependency in probabilistic safety assessment

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ARTICLE INFO

Article history:
Received 13 April 2022
Received in revised form
26 July 2022
Accepted 27 August 2022
Available online xxx

Keywords:
Fault tree
Dependency
Human failure event
Probabilistic safety assessment
If-then-else logic

ABSTRACT

Among the various elements of probabilistic safety assessment (PSA), human failure events (HFEs) and their dependencies are major contributors to the quantification of risk of a nuclear power plant. Currently, the dependency among HFEs is reflected using a post-processing method in PSA, wherein several drawbacks, such as limited propagation of minimal cutsets through the fault tree and improper truncation of minimal cutsets exist. In this paper, we propose a method to model the HFE dependency directly in a fault tree using the if-then-else logic. The proposed method proved to be equivalent to the conventional post-processing method while addressing the drawbacks of the latter. We also developed a software tool to facilitate the implementation of the proposed method considering the need for modeling the dependency between multiple HFEs. We applied the proposed method to a specific case to demonstrate the drawbacks of the conventional post-processing method and the advantages of the proposed method. When applied appropriately under specific conditions, the direct fault-tree modeling of HFE dependency enhances the accuracy of the risk quantification and facilitates the analysis of minimal cutsets.

1. Introduction

Several countries rely on probabilistic safety assessment (PSA) to support the subsidiary criteria of safety goals of nuclear power plants [1]. Fault tree analysis, which is an important technique in PSA, has been studied in the aerospace and nuclear industries since the 1960s [2]. Particularly, the release of WASH-1400 [3] led to the risk estimation of a nuclear power plant using fault tree analysis. In 1981, NUREG-0492 [4] outlined the guidelines to perform fault tree analysis, and NASA [5] published an updated report in 2002.

As human error is a major contributing factor to risk, Swain et al. [6] provide detailed information on the analysis of human error and general guidelines for human reliability analysis (HRA) based on PSA's fundamental terms. NUREG-1792 [7] compares the requirements of the American Society of Mechanical Engineers (ASME) PSA standard [8] and those of the Nuclear Energy Institute (NEI) PSA peer review guidance [9] to outline the appropriate practices to be followed when performing HRA, which forms the basis of the Regulatory Guide 1.200 [10].

Several HRA methods, such as Technique for Human Error Rate Prediction (THERP) [6], Accident Sequence Evaluation Program (ASEP) [11] and Standardized Plant Analysis Risk HRA (SPAR-H) [12] are widely employed in practical applications. In Korea, a standard HRA method called K-HRA was developed [13]. Furthermore, NUREG-1842 [14] evaluates various HRA methods, and a publication by Park et al. [15] presents a comparison of the representative methods in terms of quantitative aspects.

During HRA, the dependency between human failure events (HFEs) must be considered because the quantification results may be underestimated if the dependency of multiple HFEs is not examined properly in minimal cutsets. Additionally, the ASME/ANS PSA Standard [8] and NEI PSA peer review guidance [9] suggest that the dependency between HFEs must be considered. Currently, the dependency of HFEs is reflected using a post-processing method after minimal cutsets are generated. Recently, Arigi et al. [16] developed an HFE dependency analysis method considering multi-unit event scenarios. Herberger and Boring [17] reported alternative dependence equations that follow the laws of probability.

INL/EXT-20-59202 [18] provides key issues regarding PSA tools and methods. The report ranks the dependency analysis for human reliability analysis as the second issue followed by quantification

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https://doi.org/10.1016/j.net.2022.08.029

speed and efficiency. One of major issues associated with the dependency analysis is the computational burden issue caused by setting HEPs to an artificially high value to avoid inappropriate truncation of minimal cutsets that are not supposed to be truncated. Another major issue is the inability of displaying the failure path for a post-processed minimal cutset in a fault tree because the post-processing replaces original HFEs with dependent events.

In this paper, we propose a method for direct fault-tree modeling of the dependency between HFEs. It reflects the HFE dependency directly in a fault tree model using the if-then-else logic and addresses the drawbacks of the conventional post-processing method. The remainder of this paper is organized as follows. Section 2 explains HFEs and their dependencies in PSA. Section 3 introduces the direct fault-tree modeling of HFE dependency and outlines the benefits of the proposed method. Additionally, the software tool developed to facilitate the implementation of the proposed method is described in Section 3. Section 4 presents the application of the proposed method to a specific case. Finally, Section 5 concludes the paper.

2. HFEs in PSA

2.1. HFEs in PSA model

In the case of a nuclear power plant, HFEs in PSA may cause initiating events or failure in performing the required actions to shut down the plant safely after an initiating event. NUREG-1792 [7] categorizes HFEs into three types, namely pre-initiator HFEs, human-induced initiators, and post-initiator HFEs. Pre-initiator HFEs occur under normal operating conditions and include HFEs in calibration, test, and maintenance. Human-induced initiators are incorporated in the analysis of initiating event frequency and therefore not explicitly modeled in fault trees. Post-initiator HFEs occur in transient conditions and include emergency, backup, and recovery actions [13].

Emergency actions refer to those operator actions that are used for accident mitigation. Emergency actions are performed to execute a safety function, and the operator actions are modeled using an OR logic with the hardware failures of the corresponding safety function in a fault tree. Failure to perform emergency actions causes failure of the safety function. Emergency actions include the HFEs in feed-and-bleed and aggressive cooldown operations.

Backup actions involve performing a safety function in addition to automatic generation of an actuation signal. In this study, the operator actions are modeled using an AND logic with the primary methods of executing the safety function, such as automatic actuation signal generation. This implies that the safety function is unavailable when both the automatic signal actuation and the operator's backup action fail.

Recovery actions include the recovery of failed motor-operated valves by a field operator. Recovery actions are considered during the post-processing of minimal cutsets, depending on accident sequences.

HFEs grouped from a conservative perspective can be modeled as a single event at a higher level, such as the failure of a system or a function when the impacts of HFEs are similar. This is considered an appropriate practice of HFE modeling [7] to effectively reveal the outcome of HFEs in the PSA model. Additionally, HFEs must be modeled in a location close to the relevant component, system, and function. For instance, the actions required to initiate the safety injection pump for feed operation and open the pressurizer pilot-operated relief valves for bleed operation are typically grouped into a single event, which formulates the feed-and-bleed operation.

2.2. Dependency between HFEs

Success or failure of operator actions may affect their subsequent actions, which is referred to as the dependency between HFEs. Therefore, not considering the dependency of HFEs may result in the underestimation of the impact of HFEs. The dependency of HFEs exists between detailed tasks for an event or HFEs in an accident sequence [16]. The dependency in the former case involves substantial subjectivity and is evaluated as either independent or completely dependent [13] [19], whereas the dependency in the latter case is evaluated using the combinations of HFEs identified within minimal cutsets.

The level of dependency between HFEs is determined based on dependency rules. THERP and SPAR-H include five dependency levels from zero dependence to complete dependence [6] [12], whereas ASEP includes three levels [11]. The conditional probabilities of the subsequent dependent HFEs are derived using the formula provided in THERP [6] based on determined dependency levels.

In an accident sequence involving two or more HFEs, the probabilities of subsequent HFEs must be recalculated by reflecting the dependency level. Additionally, the event names of the subsequent HFEs are changed to distinguish them from independent HFEs or HFEs with different dependency levels.

Fig. 1 illustrates the conventional and proposed methods that are used to reflect HFE dependency. The event and fault trees in Fig. 1 are also provided in Section 4. The conventional method involves post-processing of the minimal cutsets, which are generated without reflecting HFE dependency in the single top model that combines event and fault trees. Owing to the application of the truncation limit before reflecting the HFE dependency, improperly truncated minimal cutsets exist, which may not have been truncated if the dependency had been reflected prior to the application of the truncation limit. A technique to reduce such improper truncation is to set HEPs to an artificially high value (usually 0.1 or 1.0), but it may cause the quantification speed issue, as mentioned in INL/EXT-20-59202 [18].

The post-processing is performed by fault tree solvers, such as Fault Tree Reliability Evaluation eXpert (FTREX) [20]. In Fig. 1, *OPSFWP* and *OPFB* are two HFEs, wherein the occurrence of *OPSFWP* affects the occurrence probability of *OPFB*. In other words, *OPFB* is a subsequent HFE of *OPSFWP*. The event *OPFB* may be substituted by another event, *OPFBDEP*, whose probability is assigned based on the dependency level of *OPFB* on *OPSFWP*.

Eq. (1) presents the post-processing rule used in AIMS-PSA [21]. AIMS-PSA is an integrated PSA modeling and analysis software packagelike SAREX, RiskSpectrum, RISKMAN, CAFTA, and SAPHIRE. The post-processing rule in Eq. (1) means that when two HEPs, both *OPSFWP* and *OPFB*, exist in a minimal cutset, *OPFB* is substituted to *OPFBDEP*. Similar post-processing rules exist in other PSA software packages. The absence of *OPSFWP* in a minimal cutset retains *OPFB* in the minimal cutset, whereas the presence of *OPSFWP* results in the substitution of *OPFBDEP* for *OPFB* with a newly assigned probability. As the dependent event (*OPFBDEP*) does not exist in the single top model (a fault tree), the single top model cannot correctly display the failure path for a minimal cutset comprising *OPFBDEP*, as mentioned in INL/EXT-20-59202 [18].

$$OPSFWP, OPFB \ / \ OPSFWP, \ OPFBDEP. \tag{1}$$

To overcome the drawbacks of this post-processing method, we propose a novel method of reflecting the HFE dependency by directly modeling the dependency in the fault tree, as illustrated in Fig. 1. The proposed method is applied after HRA practitioners determine dependency levels and HEPs with dependency

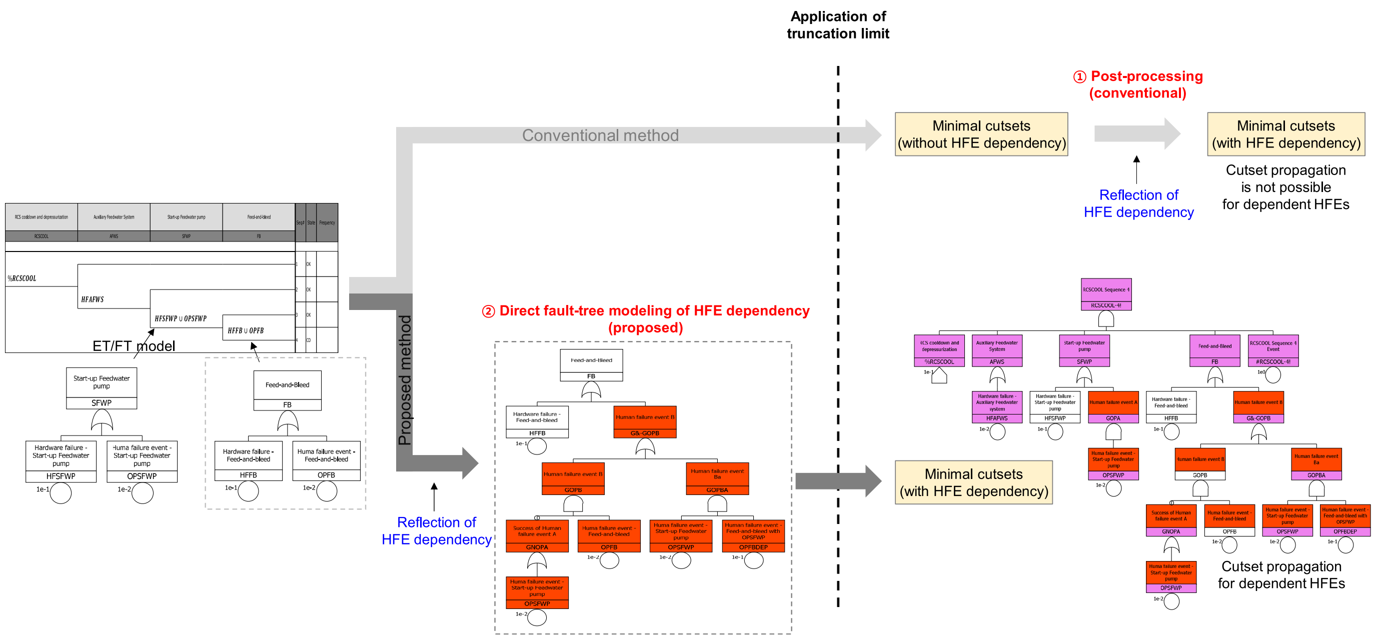

Fig. 1. Comparison of the conventional and proposed methods used to reflect HFE dependency.

considerations are calculated. In the proposed method, all minimal cutsets with HFE dependency are generated without improperly truncated ones as the dependency is reflected prior to the minimal cutset generation and application of the truncation limit. Additionally, the failure path for a minimal cutset comprising *OPFBDEP* can be corrected displayed in the single top model as the dependent event (*OPFBDEP*) exists in the single top model. Thus, the proposed direct fault-tree modeling of HFE dependency overcomes the drawbacks of the conventional post-processing method, such as improper truncation of minimal cutsets and inability to display the failure path for a minimal cutset that comprise dependent events. The advantages of the proposed method are described in detail considering a specific case in Section 4.

3. Direct fault-tree modeling of HFE dependency

This section describes the direct modeling of HFE dependency in a fault tree. HFEs are represented by the events A, B, C, and D in terms of their order in accident mitigation. The order of HFEs is identified during the dependency analysis of HFEs considering the emergency operating procedures. Boolean logic used to model failures of hardware, test and maintenance, and other failures is represented by X, Y, Z, and W. We assumed that the HFEs are not included in these Boolean logics.

3.1. Dependency between two HFEs

Failure of an operator's emergency action results in the failure of the corresponding safety function. Therefore, the failure of the safety function with an operators' emergency action is modeled in a fault tree using an OR logic of an HFE and a Boolean logic. Considering two operators' emergency actions A and B and two Boolean logics X and Y of two safety functions, the Boolean expression for the simultaneous failure of the two safety functions with the post-processing of minimal cutsets is obtained as

$$(A+X)(B+Y) = AB + AY + BX + XY \Rightarrow AB_A + AY + BX + XY \tag{2}$$

where "⇒" indicates the post-processing of minimal cutsets, which substitutes AB with AB_A in Eq. (2). Herein, B_A denotes the HFE after reflecting the dependency of B on A. The upper part of Fig. 2 depicts the conventional post-processing of minimal cutsets given in Eq. (2).

The primary idea behind the direct fault-tree modeling of HFE dependency is to substitute B with B' in a fault tree before minimal cutsets are generated, wherein B' is defined as

$$B = \overline{A}B + AB \rightarrow \overline{A}B + AB_A = B' \tag{3}$$

where "→" indicates the application of the direct fault-tree modeling of HFE dependency and $\overline{A}$ represents the success event of A. The first and second terms in Eq. (3), namely $\overline{A}B$ and AB_A, denote the logical AND operations without and with A, respectively.

Substituting B with B' using the proposed direct fault-tree modeling of HFE dependency, the Boolean logic for the simultaneous failure of the two functions is obtained as

$$\begin{aligned}(A+X)(B+Y) &\rightarrow (A+X)\left(\overline{A}B + AB_A + Y\right) = A\overline{A}B + AB_A + AY \\ &+ \overline{A}BX + AB_AX + XY = AB_A + AY + \overline{A}BX \\ &+ XY \approx AB_A + AY + BX + XY\end{aligned} \tag{4}$$

where "≈" indicates the application of the delete-term approximation, which is used in most fault-tree solvers by default. In Eq. (4), $A\overline{A}B$ is deleted by the complement law and AB_AX is absorbed by AB_A based on the absorption law of Boolean algebra. Furthermore, $\overline{A}BX$ is approximated to BX after applying the delete-term approximation. The lower part of Fig. 2 depicts the proposed direct fault tree modeling of HFE dependency.

Based on the comparison of two different approaches of reflecting the dependency of A and B, we identified that the results

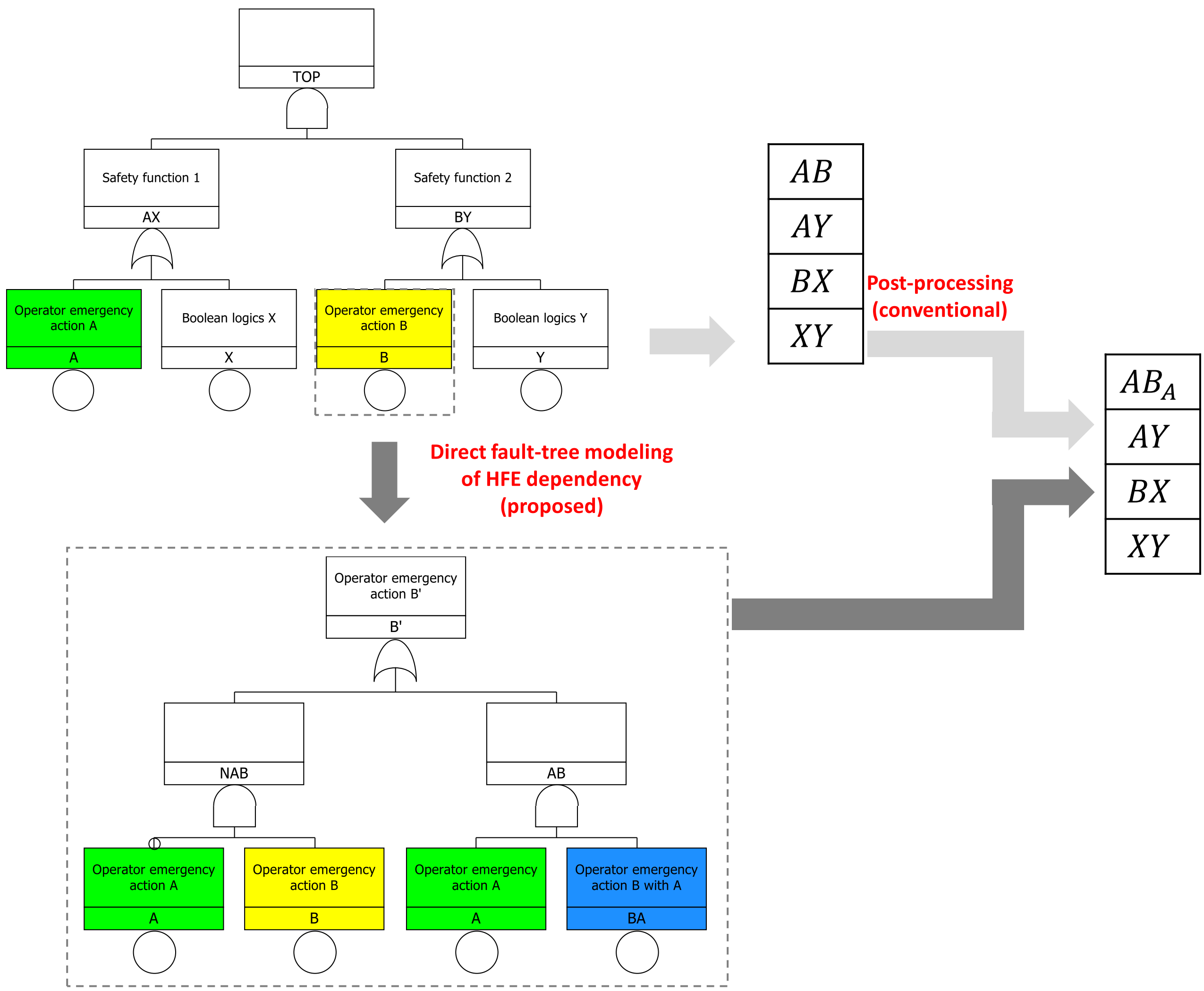

Fig. 2. Comparison between the conventional post-processing method and the and proposed direct fault tree method.

obtained from the proposed direct fault-tree modeling of HFE dependency (Eq. (4)) concur with those obtained from the conventional post-processing of minimal cutsets (Eq. (2)) as illustrated in Fig. 2.

However, the substitution of B' for B may not produce equivalent results for operator actions other than emergency action. When a safety function is not composed of an emergency action, nonsense minimal cutsets may occur. For instance, when the preceding HFE is not included, the minimal cutsets after post-processing are as follows.

$$X(B+Y) = BX + XY \Rightarrow BX + XY \tag{5}$$

In Eq. (5), no minimal cutset reflects the dependency of B on A owing to the absence of a preceding HFE, which is A. In this case, only two minimal cutsets are obtained; however, the substitution of B with B' results in three minimal cutsets as indicated in Eq. (6). The second term of Eq. (6), AB_AX, is a nonsense minimal cutset.

$$X(B+Y) \rightarrow X\left(\bar{A}B + AB_A + Y\right) = \bar{A}BX + AB_AX + XY = \bar{A}BX + AB_AX + XY \approx BX + AB_AX + XY \tag{6}$$

We considered another example, wherein the preceding HFE is a backup action and modeled using an AND logic, such as $AZ + X$. In this case, the minimal cutsets after post-processing are obtained as

$$(AZ+X)(B+Y) = ABZ + AYZ + BX + XY \rightarrow AB_AZ + AYZ + BX + XY \tag{7}$$

Substituting B with B' results in the minimal cutsets as depicted in Eq. (8), wherein the first, second, third, and fifth terms are equivalent to the first, second, third, and fourth terms of Eq. (7), respectively. When the complement law of Boolean algebra and the delete-term approximation are applied to Eq. (8), the fourth term, AB_AX, is identified as a nonsense minimal cutset.

$$(AZ+X)(B+Y) \rightarrow (AZ+X)\left(\bar{A}B + AB_A + Y\right) = A\bar{A}BZ + AB_AZ + AYZ + \bar{A}BX + AB_AX + XY = AB_AZ + AYZ + \bar{A}BX + AB_AX + XY \approx AB_AZ + AYZ + BX + AB_AX + XY \tag{8}$$

Because nonsense minimal cutsets may occur in other cases, this study considers the application of the proposed method to only those cases of emergency actions.

3.2. Dependency between more than two HFEs

Considering three operator emergency actions A, B, and C and three Boolean logics X, Y, and Z of three safety functions, the Boolean logic for simultaneous failure of the three safety functions with the post-processing of minimal cutsets is obtained as

$$\begin{aligned}(A+X)(B+Y)(C+Z) = {} & ABC+ABZ+ACY+AYZ+BCX+BXZ \\ & +CXY+XYZ \Rightarrow AB_AC_{AB}+AB_AZ+AC_AY \\ & +AYZ+BC_BX+BXZ+CXY+XYZ\end{aligned} \tag{9}$$

where C_A, C_B, and C_{AB} are the HFEs after reflecting the dependency of C on A, B, and AB_A, respectively.

In the direct fault-tree modeling of HFE dependency, B is substituted with B' in Eq. (3) and C is substituted with C', where C' is defined as

$$C' = \bar{A}\bar{B}C + \bar{A}BC_B + A\overline{B_A}C_A + AB_AC_{AB} \tag{10}$$

When the proposed direct fault-tree modeling of HFE dependency is used, the Boolean logic for the simultaneous failure of the three safety functions is

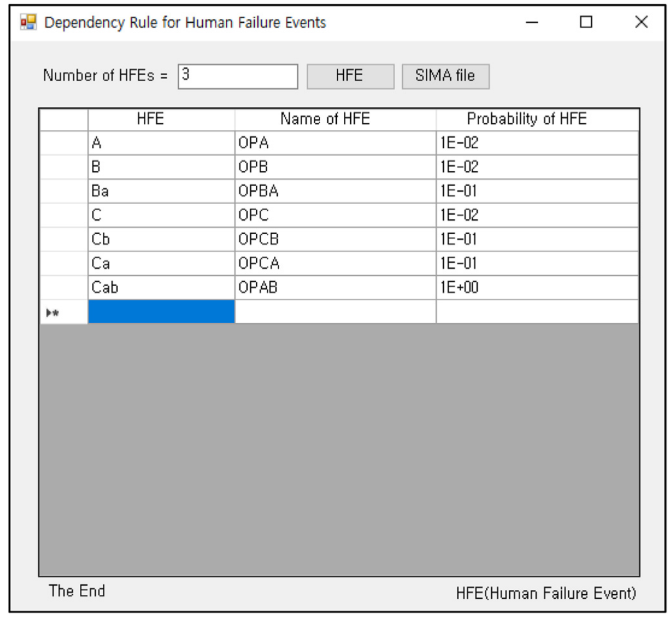

Fig. 3. Input to the software tool for fault tree modeling of HRA dependency.

$$\begin{aligned}(A+X)(B+Y)(C+Z) \rightarrow {} & (A+X)\left(\bar{A}B+AB_A+Y\right)\left(\bar{A}\bar{B}C+\bar{A}BC_B+A\overline{B_A}C_A+AB_AC_{AB}+Z\right)=\left(AB_A+AY+\bar{A}BX+XY\right) \\ & \left(\bar{A}\bar{B}C+\bar{A}BC_B+A\overline{B_A}C_A+AB_AC_{AB}+Z\right)=A\bar{A}B\bar{B}C+A\bar{A}BC_B+A\bar{A}B\overline{B_A}C_A+A\bar{A}BB_AC_{AB}+A\bar{A}BZ+A\bar{A}\bar{B}B_AC+A\bar{A}BB_AC_B \\ & +AB_A\overline{B_A}C_A+AB_AC_{AB}+AB_AZ+A\bar{A}\bar{B}CY+A\bar{A}BC_BY+A\overline{B_A}C_AY+AB_AC_{AB}Y+AYZ+\bar{A}B\bar{B}CX+\bar{A}BC_BX+A\bar{A}B\overline{B_A}C_AX \\ & +A\bar{A}BB_AC_{AB}X+\bar{A}BXZ+A\bar{A}\bar{B}B_ACX+A\bar{A}BB_AC_BX+AB_A\overline{B_A}C_AX+AB_AC_{AB}X+AB_AXZ+\bar{A}\bar{B}CXY+\bar{A}BC_BXY+A\overline{B_A}C_AXY \\ & +AB_AC_{AB}XY+XYZ=AB_AC_{AB}(1+Y+X+XY)+AB_AZ(1+X)+A\overline{B_A}C_AY(1+X)+AYZ+\bar{A}BC_BX(1+Y)+\bar{A}BXZ \\ & +\bar{A}\bar{B}CXY+XYZ=AB_AC_{AB}+AB_AZ+A\overline{B_A}C_AY+AYZ+\bar{A}BC_BX+\bar{A}BXZ+\bar{A}\bar{B}CXY+XYZ\approx AB_AC_{AB}+AB_AZ+AC_AY \\ & +AYZ+BC_BX+BXZ+CXY+XYZ\end{aligned} \tag{11}$$

The complement law, absorption law, and the delete-term approximation are applied to derive Eq. (11), which is equivalent to Eq. (9).

Similarly, considering four operator emergency actions A, B, C, and D and four Boolean logics X, Y, Z, and W of four safety functions, the Boolean logic for simultaneous failure of the four safety functions with the post-processing of minimal cutsets is obtained as

where D_A, D_B, D_C, D_{AB}, D_{AC}, D_{BC}, and D_{ABC} are the HFEs after reflecting the dependency of D on A, B, C, AB_A, AC_A, BC_B, and AB_AC_{AB}, respectively.

In the direct fault-tree modeling of HFE dependency, B and C are substituted with B' and C' in Eqs. (3) and (10), respectively, and D is substituted with D', where D' is defined as

$$\begin{aligned}(A+X)(B+Y)(C+Z)(D+W) = {} & ABCD+ABCW+ABDZ+ABZW+ACDY+ACYW+ADYZ+AYZW+BCDX+BCXW+BDXZ+BXZW \\ & +CDXY+CXYW+DXYZ+XYZW \Rightarrow AB_AC_{AB}D_{ABC}+AB_AC_{AB}W+AB_AD_{AB}Z+AB_AZW+AC_AD_{AC}Y \\ & +AC_AYW+AD_AYZ+AYZW+BC_BD_{BC}X+BC_BXW+BD_BXZ+BXZW+CD_CXY+CXYW+DXYZ+XYZW\end{aligned} \tag{12}$$

$$\begin{aligned} D' = {} & \overline{A}\,\overline{B}\,\overline{C}D + \overline{A}\,\overline{B}CD_C + \overline{A}B\overline{C_B}D_B + \overline{A}BC_BD_{BC} + A\overline{B_AC_A} + A\overline{B_A}C_AD_{AC} \\ & + AB_A\overline{C_{AB}}D_{AB} + AB_AC_{AB}D_{ABC} \end{aligned} \tag{13}$$

Therefore, when the proposed direct fault-tree modeling of HFE dependency is used, the Boolean logic for the simultaneous failure of the four safety functions is

$$\begin{aligned}
(A+X)(B+Y)(C+Z)(D+W) \\
\rightarrow {} & (A+X)\left(\overline{A}B + AB_A + Y\right)\left(\overline{A}\,\overline{B}C + \overline{A}BC_B + A\overline{B_A}C_A + AB_AC_{AB}\right. \\
& \left.+Z\right)\left(\overline{A}\,\overline{B}\,\overline{C}D + \overline{A}\,\overline{B}CD_C + \overline{A}B\overline{C_B}D_B + \overline{A}BC_BD_{BC} + A\overline{B_AC_A}D + A\overline{B_A}C_AD_{AC}\right. \\
& \left.+ AB_A\overline{C_{AB}}D_{AB} + AB_AC_{AB}D_{ABC} + W\right) \\
= {} & \left(AB_AC_{AB} + AB_AZ + A\overline{B_A}C_AY + AYZ + \overline{A}BC_BX + \overline{A}BXZ + \overline{A}\,\overline{B}CXY\right. \\
& \left.+ XYZ\right)\left(\overline{A}\,\overline{B}\,\overline{C}D + \overline{A}\,\overline{B}CD_C + \overline{A}B\overline{C_B}D_B + \overline{A}BC_BD_{BC} + A\overline{B_AC_A}D\right. \\
& \left.+ A\overline{B_A}C_AD_{AC} + AB_A\overline{C_{AB}}D_{AB} + AB_AC_{AB}D_{ABC} + W\right) \\
= {} & A\overline{A}\,\overline{B}B_A\overline{C}C_{AB}D + A\overline{A}\,\overline{B}B_ACC_{AB}D_C + A\overline{A}BB_A\overline{C_B}C_{AB}D_B + A\overline{A}BB_AC_BC_{AB}D_{BC} + AB_A\overline{B_AC_A}C_{AB}D \\
& + AB_A\overline{B_A}C_AC_{AB}D_{AC} + AB_AC_{AB}\overline{C_{AB}}D_{AB} + AB_AC_{AB}D_{ABC} + AB_AC_{AB}W + A\overline{A}\,\overline{B}B_A\overline{C}DZ + A\overline{A}\,\overline{B}B_ACD_CZ \\
& + A\overline{A}BB_A\overline{C_B}D_BZ + A\overline{A}BB_AC_BD_{BC}Z + AB_A\overline{B_AC_A}DZ + AB_A\overline{B_A}C_AD_{AC}Z + AB_A\overline{C_{AB}}D_{AB}Z + AB_AC_{AB}D_{ABC}Z \\
& + AB_AZW + A\overline{A}\,\overline{BB_A}\,\overline{C}C_ADY + A\overline{A}\,\overline{BB_A}CC_AD_CY + A\overline{A}B\overline{B_A}C_A\overline{C_B}D_BY + A\overline{A}B\overline{B_A}C_AC_BD_{BC}Y + A\overline{B_A}C_A\overline{C_A}DY \\
& + A\overline{B_A}C_AD_{AC}Y + AB_A\overline{B_A}C_A\overline{C_{AB}}D_{AB}Y + AB_A\overline{B_A}C_AC_{AB}D_{ABC}Y + A\overline{B_A}C_AYW + A\overline{A}\,\overline{B}\,\overline{C}DYZ + A\overline{A}\,\overline{B}CD_CYZ \\
& + A\overline{A}B\overline{C_B}D_BYZ + A\overline{A}BC_BD_{BC}YZ + A\overline{B_AC_A}DYZ + A\overline{B_A}C_AD_{AC}YZ + AB_A\overline{C_{AB}}D_{AB}YZ + AB_AC_{AB}D_{ABC}YZ \\
& + AYZW + \overline{A}B\overline{B}\,\overline{C}C_BDX + \overline{A}B\overline{B}CC_BD_CX + \overline{A}B\overline{C_B}C_BD_BX + \overline{A}BC_BD_{BC}X + A\overline{A}B\overline{B_AC_A}C_BDX \\
& + A\overline{A}B\overline{B_A}C_AC_BD_{AC}X + A\overline{A}BB_AC_B\overline{C_{AB}}D_{AB}X + A\overline{A}BB_AC_BC_{AB}D_{ABC}X + \overline{A}BC_BXW + \overline{A}B\overline{B}\,\overline{C}DXZ \\
& + \overline{A}B\overline{B}CD_CXZ + \overline{A}B\overline{C_B}D_BXZ + \overline{A}BC_BD_{BC}XZ + A\overline{A}B\overline{B_AC_A}DXZ + A\overline{A}B\overline{B_A}C_AD_{AC}XZ + A\overline{A}BB_A\overline{C_{AB}}D_{AB}XZ \\
& + A\overline{A}BB_AC_{AB}D_{ABC}XZ + \overline{A}BXZW + \overline{A}\,\overline{B}\,\overline{C}CDXY + \overline{A}\,\overline{B}CD_CXY + \overline{A}B\overline{B}C\overline{C_B}D_BXY + \overline{A}B\overline{B}CC_BD_{BC}XY \\
& + A\overline{A}\,\overline{BB_A}C\overline{C_A}DXY + A\overline{A}\,\overline{BB_A}CC_AD_{AC}XY + A\overline{A}\,\overline{B}B_AC\overline{C_{AB}}D_{AB}XY + A\overline{A}\,\overline{B}B_ACC_{AB}D_{ABC}XY + \overline{A}\,\overline{B}CXYW \\
& + \overline{A}\,\overline{B}\,\overline{C}DXYZ + \overline{A}\,\overline{B}CD_CXYZ + \overline{A}B\overline{C_B}D_BXYZ + \overline{A}BC_BD_{BC}XYZ + A\overline{B_AC_A}DXYZ + A\overline{B_A}C_AD_{AC}XYZ \\
& + AB_A\overline{C_{AB}}D_{AB}XYZ + AB_AC_{AB}D_{ABC}XYZ + XYZW = AB_AC_{AB}D_{ABC}(1+Z+YZ+XYZ) + AB_AC_{AB}W \\
& + AB_A\overline{C_{AB}}D_{AB}Z(1+Y+XY) + AB_AZW + A\overline{B_A}C_AD_{AC}Y(1+Z+XZ) + A\overline{B_A}C_AYW + A\overline{B_AC_A}DYZ(1+X) + AYZW \\
& + \overline{A}BC_BD_{BC}X(1+Z+YZ) + \overline{A}BC_BXW + \overline{A}B\overline{C_B}D_BXZ(1+Y) + \overline{A}BXZW + \overline{A}\,\overline{B}CD_CXY(1+Z) + \overline{A}\,\overline{B}CXYW \\
& + \overline{A}\,\overline{B}\,\overline{C}DXYZ + XYZW = AB_AC_{AB}D_{ABC} + AB_AC_{AB}W + AB_A\overline{C_{AB}}D_{AB}Z + AB_AZW + A\overline{B_A}C_AD_{AC}Y + A\overline{B_A}C_AYW \\
& + A\overline{B_AC_A}DYZ + AYZW + \overline{A}BC_BD_{BC}X + \overline{A}BC_BXW + \overline{A}B\overline{C_B}D_BXZ + \overline{A}BXZW + \overline{A}\,\overline{B}CD_CXY \\
& + \overline{A}\,\overline{B}CXYW + \overline{A}\,\overline{B}\,\overline{C}DXYZ + XYZW \approx AB_AC_{AB}D_{ABC} + AB_AC_{AB}W + AB_AD_{AB}Z + AB_AZW \\
& + AC_AD_{AC}Y + AC_AYW + ADYZ + AYZW + BC_BD_{BC}X + BC_BXW \\
& + BD_BXZ + BXZW + CD_CXY + CXYW + DXYZ + XYZW
\end{aligned} \tag{14}$$

The complement law, absorption law, and the delete-term approximation are applied to derive Eq. (14), which is equivalent to Eq. (12).

Therefore, Eqs. (4), (11), and (14) verify that the results of two, three, and four HFEs, respectively, obtained through the proposed direct fault-tree modeling of HFE dependency concur with those obtained from the conventional method of post-processing of minimal cutsets. Thus, by defining the dependent HFEs appropriately as depicted in Eqs. (3), (10), and (13), the equivalence of results can be validated for a simultaneous failure of a higher number of safety functions. Herein, each safety function is modeled using an OR logic of an HFE for emergency action and Boolean logics to model other failures such as hardware failures, test and maintenance, and others.

Typically, tracing the combination of failures that leads to the top event in the fault tree is challenging in the case of conventional post-processing of minimal cutsets. Conversely, direct fault-tree modeling of HFE dependency aids in identifying the failure path that leads to the top event in a fault tree, which is the core damage

Value	OPA	0.01				
Value	OPB	0.01				
Value	OPBA	0.1				
Value	OPC	0.01				
Value	OPCB	0.1				
Value	OPCA	0.1				
Value	OPCAB	1				
Set	OPA	GOPA				
Set	OPB	GOPB				
Set	OPC	GOPC				
Gate	GNOPA		+	OPA		
Gate	GNOPB		+	OPB		
Gate	GNOPBA		+	OPBA		
Gate	GNOPC		+	OPC		
Gate	GNOPCB		+	OPCB		
Gate	GNOPCA		+	OPCA		
Gate	GNOPCAB		+	OPCAB		
Gate	GOPA		*	OPA		
Gate	GOPB		*	-GNOPA	OPB	
Gate	GOPBA		*	OPA	OPBA	
Gate	GOPC		*	-GNOPA	-GNOPB	OPC
Gate	GOPCB		*	-GNOPA	OPB	OPCB
Gate	GOPCA		*	OPA	-GNOPBA	OPCA
Gate	GOPCAB		*	OPA	OPBA	OPCAB
Add+	GOPB	GOPBA				
Add+	GOPC	GOPCB		GOPCA	GOPCAB	

Fig. 4. SIMA script considering an example of three HFEs.

event in a single top fault tree that combines all event and fault trees of Level 1 PSA.

Additionally, improper truncation of minimal cutsets is common in the conventional post-processing of minimal cutsets. For instance, a virtually infinite number of minimal cutsets is generated [22] to estimate the risk of a nuclear power plant in large fault trees. Consequently, those minimal cutsets with probabilities lower than the truncation limit are truncated. As the post-processing of minimal cutsets to reflect HFE dependency is performed after the truncation, improperly truncated minimal cutsets exist. Conversely, HFE dependency is reflected prior to the truncation in the case of direct fault-tree modeling of HFE dependency, which can avoid improper truncation of minimal cutsets.

3.3. Software tool incorporating the direct fault-tree modeling of HFE dependency

When an HFE is dependent on other HFEs, all combinations of HFE dependency must be modeled in a fault tree. As indicated in Eqs. (2), (9), and (12), when n HFEs are considered, the number of HFEs and their dependency events are calculated as $2^n - 1$. In fact, the number of significant HFEs with dependency consideration found in a plant-level PSA is usually less than five, and hence the number of HFEs and their dependency events is usually limited.

We developed a software tool that automatically modifies a fault tree to reflect the dependency between HFEs. The tool determines the events required for modeling HFE dependency based on the number of HFEs. Additionally, it provides SIMA (script interpreter for mapping algorithm) script of AIMS-PSA, to modify the fault tree and reflect the HFE dependency.

Fig. 3 presents the required input to the software tool. All combinations of HFE dependency are generated in alphabetical order by entering the number of HFEs as input. For instance, when the number of HFEs is three, the combinations for A, B, C, B_a, C_a, C_b, and C_{ab} are generated in the first column of the software tool, as shown in Fig. 3. HFEs that do not reflect the dependency are A, B, and C, whereas B_a, C_a, and C_b are affected by the occurrence of another HFE; C_{ab} is affected by the occurrence of both A and B. In Fig. 3, the HEPs with dependency consideration are assumed to be one tenth of their original HEPs, i.e. the HEPs without dependency consideration. When the event name and the probability corresponding to each HFE are entered, the SIMA script that transforms the original fault tree to a modified one is generated (Fig. 4). Fig. 5 depicts the original fault tree that is transformed by the SIMA script to the modified fault tree illustrated in Fig. 6 to reflect the HFE dependency.

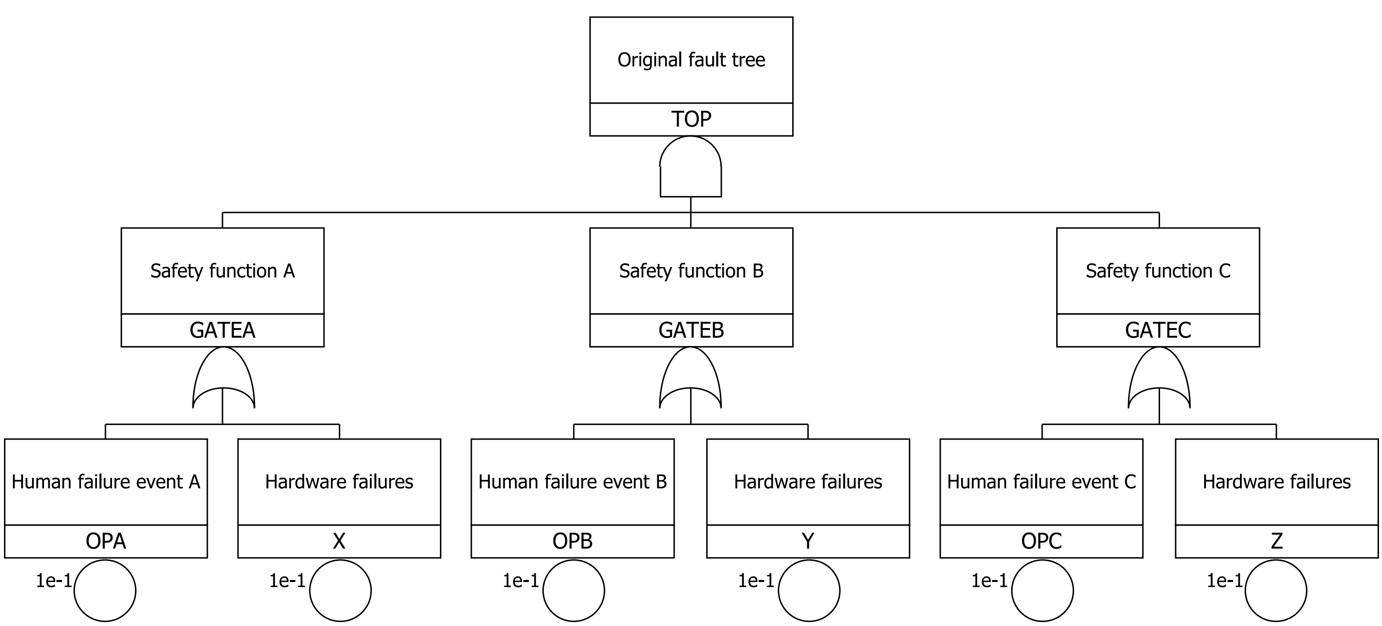

Fig. 5. Original fault tree before reflecting the HFE dependency.

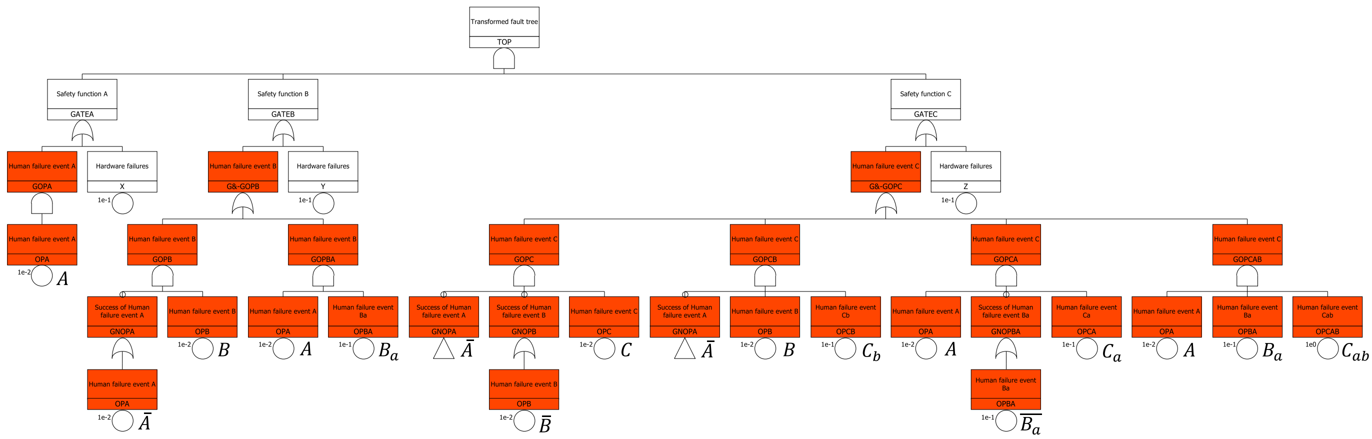

Fig. 6. Transformed fault tree after reflecting the HFE dependency.

Value	OPA	0.01			
Value	OPB	0.01			
Value	OPBA	0.1			
Value	OPC	0.01			
Value	OPCB	0.1			
Value	OPCA	0.1			
Value	OPCAB	1			
Set	OPA	GOPA			
Set	OPB	GOPB			
Set	OPC	GOPC			
Gate	GNOPA	+	OPA		
Gate	GNOPB	+	OPB		
Gate	GNOPBA	+	OPBA		
Gate	GNOPC	+	OPC		
Gate	GNOPCB	+	OPCB		
Gate	GNOPCA	+	OPCA		
Gate	GNOPCAB	+	OPCAB		
Gate	GOPA	*	OPA		
Gate	GOPB	*	-GNOPA	OPB	
Gate	GOPBA	*	OPA	OPBA	
Gate	GOPC	*	-GNOPA	-GNOPB	OPC
Gate	GOPCB	*	-GNOPA	OPB	OPCB
Gate	GOPCA	*	OPA	-GNOPBA	OPCA
Gate	GOPCAB	*	OPA	OPBA	OPCAB
Add+	GOPB	GOPBA			
Add+	GOPC	GOPCB	GOPCA	GOPCAB	

4. Application of the proposed method to a specific case

Fig. 7 depicts an event tree and Boolean logic used for the cooldown and depressurization of a reactor coolant system (RCS), which is required in most accident mitigation sequences. RCS cooldown and depressurization are performed when feedwater is supplied to the secondary system through the automatically actuated auxiliary feedwater system. If the auxiliary feedwater system is unavailable, the start-up feedwater pump can be manually started to supply the feedwater. However, the start-up feedwater may be unavailable owing to a hardware failure or an HFE. When both auxiliary and start-up feedwater pumps are unavailable, RCS cooldown and depressurization can be performed by the feed-and-bleed operation. However, as the feed-and-bleed operation also requires operator action, it may be unavailable owing to an HFE or a hardware failure [23].

We applied the proposed method to the aforementioned case to reflect the dependency of HFEs for RCS cooldown and depressurization in the single top fault tree. To focus on the effectiveness of direct fault-tree modeling of HFE dependency, the Boolean logic for hardware failures was simplified as a basic event. Table 1 presents the details of the events used.

Table 2 summarizes the quantification results obtained before and after post-processing the minimal cutsets. Four minimal

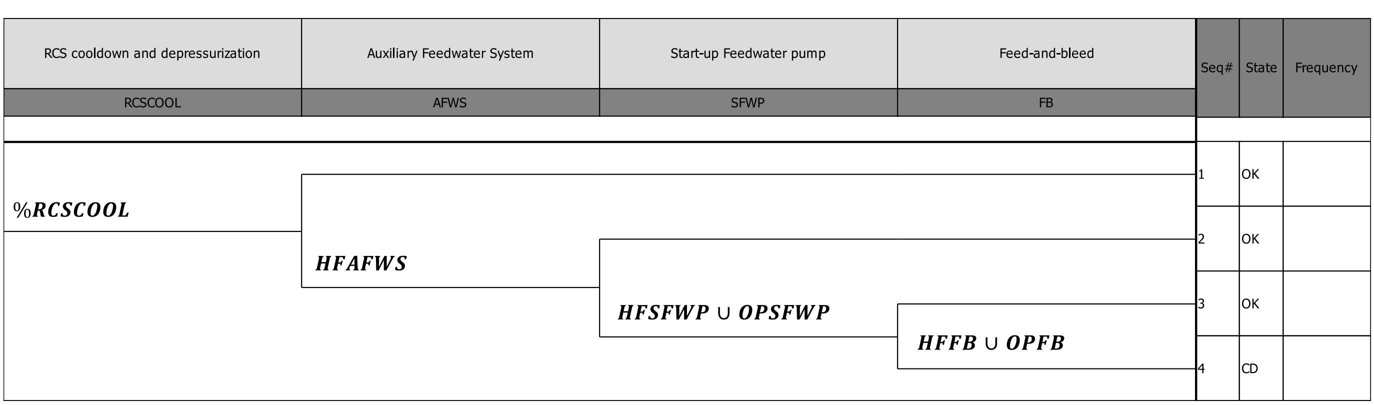

Fig. 7. Event tree and Boolean logic for the cooldown and depressurization of an RCS.

cutsets are involved in the RCS cooldown and depressurization processes. The first minimal cutset represents the sequence in which the auxiliary feedwater system, start-up feedwater pump, and feed-and-bleed operation are unavailable owing to hardware failures. The second and third minimal cutsets represent the sequences that contain one HFE, either the HFE in the case of start-up feedwater or feed-and-bleed operation. The fourth minimal cutset comprises both HFEs, wherein the HFE of the feed-and-bleed operation *OPFB* is dependent on the HFE of the start-up feedwater operation *OPSFWP*. Therefore, the probability of *OPFB* after the occurrence of *OPSFWP* must be changed to reflect the dependency. The dependent failure probability of the subsequent HFE is assumed to be 10 times its original failure probability. After post-processing, *OPFB* is replaced by *OPFBDEP*, which exhibits a failure probability of 1.00E-01. Subsequently, the frequency of the fourth minimal cutset after post-processing is 10 times the frequency before post-processing, as shown in Table 2.

Fig. 8 and Fig. 9 illustrate the fault tree for Sequence 4 in the event tree and the modified fault tree when the direct fault-tree modeling of HFE dependency is applied, respectively, through the substitution of the subsequent HFE *OPFB*, similar to Eq. (3). The success of the preceding HFE (/*OPSFWP*) is affected by the delete-term approximation owing to the NOT-logic applied to the gate (*GNOPA*) instead of the HFE itself (*OPSFWP*). If the NOT-logic is applied to the HFE (*OPSFWP*) instead of the gate (*GNOPA*), the success event is retained by the fault tree quantification engine FTREX [20] in the minimal cutset.

Table 3 presents the quantification results obtained after modifying the fault tree. Owing to the presence of *OPSFWP*, the subsequent HFE (*OPFB*) is substituted with a Boolean logic that includes the dependent HFE (*OPFBDEP*). Thus, the quantification results obtained from the direct fault-tree modeling of HFE

Table 1
Details of the events used in the example.

Event name	Description	Probability
%RCSCOOL	RCS cooldown and depressurization	1.00E-01
HFAFWS	Failure of auxiliary feedwater system owing to hardware failures, test and maintenance, and other failures	1.00E-02
HFSFWP	Failure of start-up feedwater pump owing to hardware failures, test and maintenance, and other failures	1.00E-01
HFFB	Failure of feed-and-bleed owing to hardware failures, test and maintenance, and other failures	1.00E-01
OPSFWP	HFE when operating the start-up feedwater pump	1.00E-02
OPFB	HFE during feed-and-bleed operation	1.00E-02

Table 2
Quantification results considering the specific case before and after post-processing.

	Value	BE1	BE2	BE3	BE4	Sequence
Before post-processing	1.00E-05	*%RCSCOOL*	*HFAFWS*	*HFSFWP*	*HFFB*	*#RCSCOOL – 4!*
	1.00E-06	*%RCSCOOL*	*HFAFWS*	*OPSFWP*	*HFFB*	*#RCSCOOL – 4!*
	1.00E-06	*%RCSCOOL*	*HFAFWS*	*HFSFWP*	*OPFB*	*#RCSCOOL – 4!*
	1.00E-07	*%RCSCOOL*	*HFAFWS*	*OPSFWP*	***OPFB***	*#RCSCOOL – 4!*
After post-processing	1.00E-05	*%RCSCOOL*	*HFAFWS*	*HFSFWP*	*HFFB*	*#RCSCOOL – 4!*
	1.00E-06	*%RCSCOOL*	*HFAFWS*	*OPSFWP*	*HFFB*	*#RCSCOOL – 4!*
	1.00E-06	*%RCSCOOL*	*HFAFWS*	*HFSFWP*	*OPFB*	*#RCSCOOL – 4!*
	1.00E-06	*%RCSCOOL*	*HFAFWS*	*OPSFWP*	***OPFBDEP***	*#RCSCOOL – 4!*

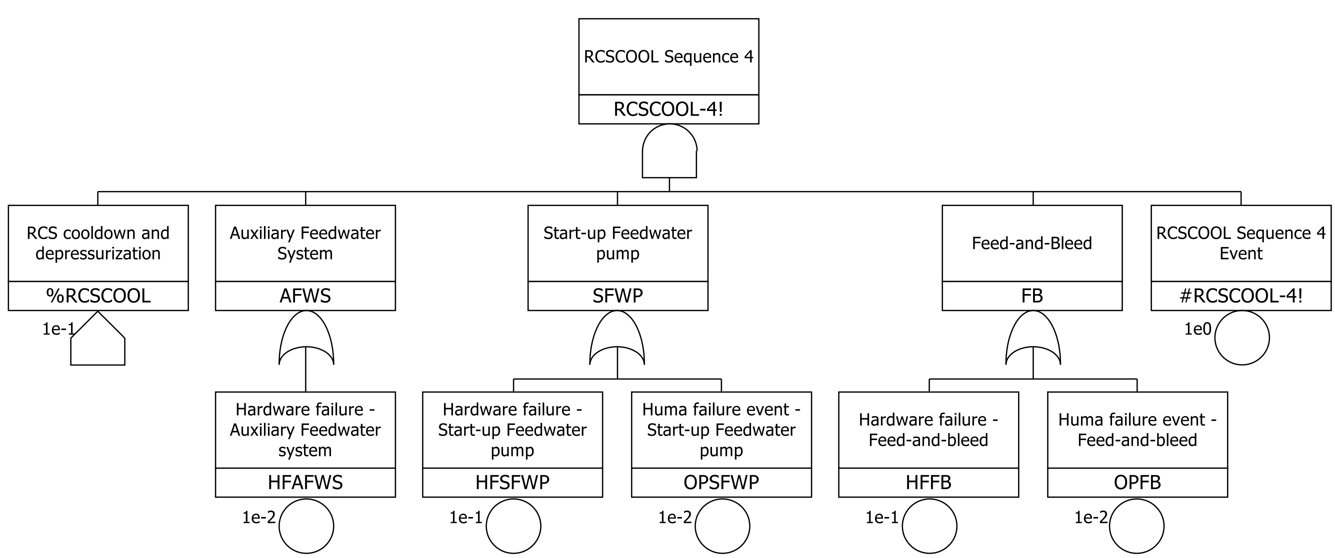

Fig. 8. Fault tree for Sequence 4 in the event tree.

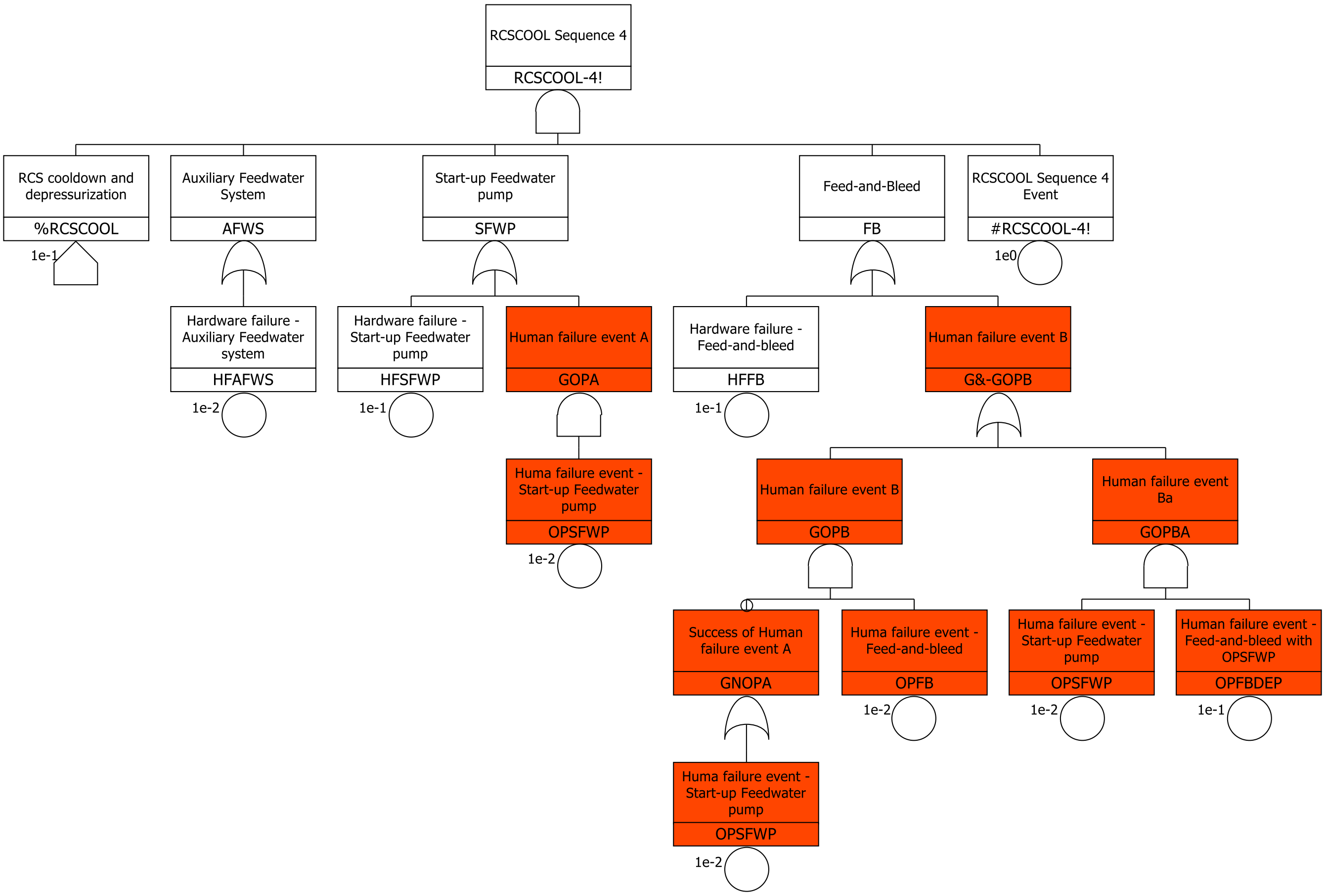

Fig. 9. Modification of fault tree for Sequence 4 in the event tree based on the direct fault-tree modeling of HFE dependency.

dependency concur with those obtained from the post-processing method.

The purple blocks in Fig. 10 depict the combination of events for the fourth minimal cutset from the direct fault-tree modeling of HFE dependency, achieved using the feature of displaying the failure path for a minimal cutset in the fault tree as presented in AIMS-PSA. The feature helps analysts identify the failure path and examine the fault tree logic. As the fault tree is a graphical representation, the failure path that leads to the top event can be identified conveniently. The failure of RCS cooldown and depressurization results from the combination of an initiating event, failures in the auxiliary feedwater system, start-up feedwater pump, and the feed-and-bleed operation. The purple blocks in Fig. 10 show that the failures of the auxiliary feedwater system, start-up feedwater pump, and feed-and-bleed operation were caused by *HFAFWS*, *OPSFWP*, and *OPFBDEP*, respectively. The ability to display the failure path for a minimal cutset with dependent HFEs is an important advantage of the proposed method with regard to analyzing the logical correctness of minimal cutsets.

A minimal cutset is truncated when its frequency is below the cut-off value, which is the truncation limit. When the conventional post-processing method is used to reflect the HFE dependency, the minimal cutsets are first derived and then the post-processing is applied. Consequently, the minimal cutsets may be improperly truncated depending on the cut-off value before the post-processing for reflecting the HFE dependency.

For instance, if the cut-off value is 1.00E-6, the fourth minimal cutset in Table 2 would be truncated before post-processing, resulting in three minimal cutsets. However, the fourth minimal cutset would not have been truncated if the dependency was reflected prior to the application of the cut-off value. Therefore, performing the post-processing after applying the cut-off value to minimal cutsets may result in improperly truncated minimal cutsets, which can underestimate the failure frequency.

Conversely, the direct fault-tree modeling of HFE dependency yields the minimal cutsets after reflecting the HFE dependency.

Table 3
Quantification results obtained using the direct fault-tree modeling method.

	Value	BE1	BE2	BE3	BE4	Sequence
Direct fault-tree modeling of HFE dependency	1.00E-05	*%RCSCOOL*	*HFAFWS*	*HFSFWP*	*HFFB*	*#RCSCOOL – 4!*
	1.00E-06	*%RCSCOOL*	*HFAFWS*	*OPSFWP*	*HFFB*	*#RCSCOOL – 4!*
	1.00E-06	*%RCSCOOL*	*HFAFWS*	*HFSFWP*	*OPFB*	*#RCSCOOL – 4!*
	1.00E-06	*%RCSCOOL*	*HFAFWS*	*OPSFWP*	***OPFBDEP***	*#RCSCOOL – 4!*

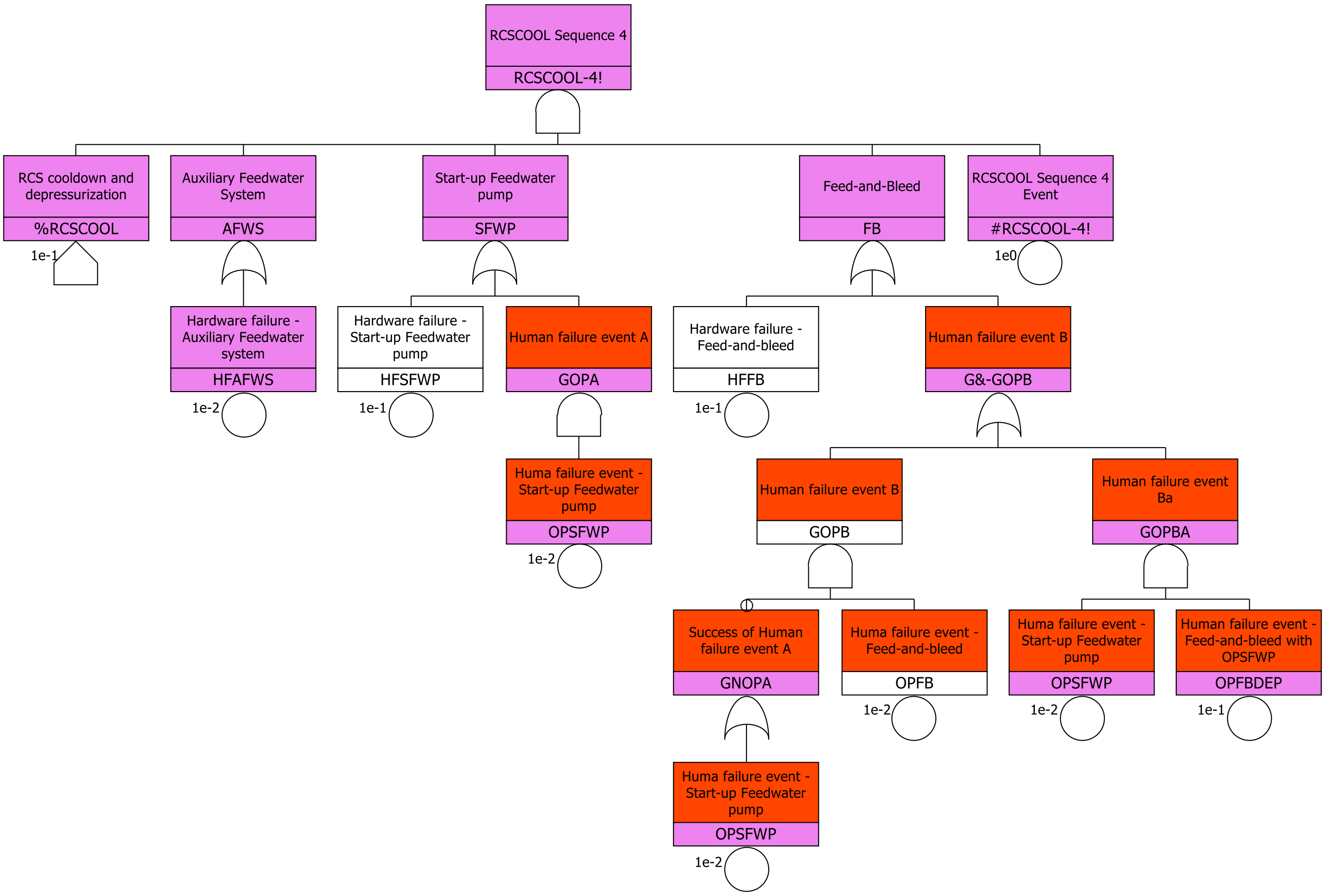

Fig. 10. Propagation of the fourth minimal cutset through the fault tree.

Consequently, improper truncation does not occur owing to the increased frequency of the minimal cutsets with HFE dependency when the cut-off value is applied to the minimal cutsets. Therefore, the four minimal cutsets in Table 3 are retained despite a cut-off value of 1.00E-6. Thus, the direct fault tree modeling of HFE dependency generates accurate minimal cutsets and determines the failure frequency corresponding to the cut-off value without improper truncation.

5. Conclusions

To address the drawbacks of the conventional post-processing method of reflecting the HFE dependency, we propose a method of directly modeling the HFE dependency in the fault tree. In the conventional method, the post-processing to reflect the HFE dependency is applied after the minimal cutsets are obtained, which restricts the display of the failure path for a post-processed minimal cutset in the fault tree. This drawback is addressed by the proposed direct fault-tree modeling of HFE dependency, which ensures the display of the failure path for a minimal cutset in the fault tree, improving the quality of a PSA model and enhancing the analysis of PSA results. Additionally, improper truncation of minimal cutsets can be avoided as the HFE dependency in the proposed method is directly modeled in the fault tree before the cut-off value is applied. Moreover, the proposed method reduces the computational burden caused by setting HEPs to an artificially high value and performing post-processing.

However, the proposed direct fault-tree modeling of HFE dependency exhibits certain limitations in its applicability based on the logic of fault trees including HFEs. We observed that nonsense minimal cutsets may be generated when the direct fault-tree modeling of HFE dependency is applied to inadequate cases. Such meaningless non-sense minimal cutsets should be removed during the review of minimal cutsets. Therefore, the proposed method is applicable when the emergency actions are modeled using OR logic with the fault trees connected to event tree branches. Also, the proposed methodology assumes that the dependency level between same HFEs is same in the same fault tree. When the dependency level of HFEs are different in the same fault tree, conventional post-processing approach should be used.

In low power and shutdown (LPSD) PSA models, multiple HFEs exist as most safety functions are operated manually, and hence, considering the HFE dependency is essential in LPSD PSA. Therefore, the proposed direct fault-tree modeling of HFE dependency is expected to be highly useful in LPSD PSA models.

To facilitate the application of the proposed method, we developed a software tool that can incorporate all combinations of HFEs and generate a script file to modify the fault tree. The tool can generate up to 15 combinations of HFEs. This is because the fault tree becomes larger exponentially as the number of HFEs grows. Therefore, we recommend the application of the proposed method to the dependency between critical HFEs because the fault tree becomes extensively large owing to the numerous HFE combinations.

When applied appropriately under specific conditions, the direct fault-tree modeling of HFE dependency can enhance the accuracy of the risk quantification and facilitate the analysis of fault tree logic and quantification results. In the future, we intend to identify a wider range of applicable conditions of the proposed method, apart from emergency actions. Moreover, a method of applying the minimum joint human-error probability when the combined probability of HFEs is below a specified minimum value must be developed. Further investigations on the possibilities and limitations of the direct fault-tree modeling of HFE dependency is essential.

Funding

This work was supported by the Nuclear Safety Research Program of the Korea Foundation of Nuclear Safety funded by the Korean government's Nuclear Safety and Security Commission [grant number 2203027-0122-CG100]; and the Nuclear Research & Development Program of the National Research Foundation of Korea funded by the Korean government's Ministry of Science and ICT [grant number NRF-2017M2B2B1071973].

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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