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A New Process for Dependency Analysis of Human Reliability Analysis

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1. Introduction

In human relaiablity analysis (HRA) of probabilistic safety assessment (PSA), human error probabilities (HEPs) of specific human failure events (HFEs) are higher than nomimal HEPs if preceding HFE(s) failed. This is due to, so called, the positive HRA dependency on the following HFE by the preceding HFE(s). Therefore, inappropriate treatment of the HRA dependency would lead to the underestimation of core damage frequency (CDF) in PSA. In this paper, a new HRA dependency analysis process is proposed that will (1) reduce the possibility of the CDF underestimation and (2) reduce quantification time to reflect HRA dependency analysis results on the model, compared to current HRA dependency analysis process. The appropriateness and effectiveness of the new process were demonstrated with an example PSA model.

2. Current HRA dependency analysis process

2.1 Steps to perform HRA dependency analsysis

With the current practice in PSA, the HRA dependency analysis process is composed of (1) HFEs combinations identification (2) Determinaiton of the level of HFEs dependency (3) Performing post-processing to reflect the HFEs dependency result.

2.2 HFEs combinations identification

The first step to perform HRA dependency analysis is to identify as many as possible HFEs combinations in the PSA model. In actual plant PSA, the HFEs combinations are identified from the cutsets generated by PSA model quantification. Therefore, it is important to modifiy PSA model for HFEs combinations not to be truncated.

At current practice, there are two methods of generating cutsets identifying as many as possible HFEs combinations. The first is to assign very high HEPs to all HFEs before quantification. The second is to lower truncation limit as low as possible. In both cases, we can get more HFEs combinations than using nominal HEPs and nominal truncation though we cannot still get some HFEs combinations. It also takes long time to quantify PSA model to get the cutsets wih HFEs combiantions for the both cases.

2.3 Determination of the level of dependency among HFEs

The essense of HRA dependency anlaysis is to determine the level of dependency for HFEs combinations identified. The level of dependency can be determined using very sophisticated process considering various human factors and performance shaping factors for each HFE of the HFEs combination. Most of the HRA methodologies provide very detailed guidance to determine the level of dependency among HFEs. In general, one of five levels of dependency is assigned for the following HFE in a HFEs combination based on the method suggested in HRA handbook. [1]

The five levels of dependency are zero dependency (ZD), low dependency (LD), medium dependency (MD), high dependency (HD) and complete dependency (CD). The HEP of following or dependent HFE in HFEs combination are as follws in Eq. (1) for each dependency level.

$$\begin{aligned} &P = P_0 \\ &P = (1 + 19*P_0)/20 \\ &P = (1 + 6*P_0)/7 \\ &P = (1 + P_0)/2 \\ &P = 1 \end{aligned} \tag{1}$$

Where, P_0 is the nominal HEP and P is the dependent HEP.

2.4 Performing post processing to reflect HFEs dependency analysis results

Once the level of HFEs dependency was determined, it is necessary to reflect HFEs dependency analysis result to the cutsets. In other words, it is necessary to change the HEPs of the HFEs with dependency from its nominal HEPs to dependent HEPs. This is generally performed using the recovery function in the PSA software. After the HEP modification for all the dependent HFEs, truncation is performed and new result is obtained.

2.5 Limitations of the current HFEs dependency analysis process

The current practice of HRA dependency analysis process has some limitations in the technical aspect. The biggest limitation is no assurance of identifying all the possible HFEs combinations with regard to the selected truncation limit in many cases. Another weakness is for PSA models to be quantified for each quantification run with the same method as the one of getting the HFEs combinations identification as described in section 2.2. This quantification run also requires long time and much computer resource.

3. A New HRA dependency analysis process

A new HRA dependency analysis process suggested in this paper is focused on (1) getting all necessary HFEs combinations with regard to the selected truncation limit and (2) performing quantification run with less time and resourece for HRA dependency analysis result reflectin into the PSA result or cutsets. The new HRA dependency analysis process is similar to the one of current practice in overall but there are some differences in details for each step. Subsections below describe the details of the new HRA dependency analysis process.

3.1 HFEs combinations idenfification

As mentioned above, a big technical limitation of current HRA dependency analysis process is that no assurance of identifying all the possible HFEs combinations in the generated cutsets. Theoretically the probability of HFEs combination is lower than or equal to the probability of the first HFE in the HFEs combination. Therefore, if we can (1) list all the HFEs in the order of time line from initiating event and (2) provide this information to quantification engine, it is assured that all the HFEs combinations for HRA dependency analysis be generated in the cutsets with regard to the selected truncation limit. This can be done for quantification engine to apply the HEP of the first HFE to the probability of the HFEs combination when performing truncation during quantificaton.

In some cases, it is not possible to list all the HFEs in the order of time line because the order of HFEs can vary with accident sequences or initiating events. In this case, the highest HEP of a HFE in the HFEs combination will be applied to the probability of the HFEs combination. These two options described above has already been implemented in the FTREX [2].

3.2 Determination of the level of dependency among HFEs

This task is exactly the same as the one of current HRA dependency analysis process.

3.3 HFEs dependency analysis result implementation into cutsets

In this paper, a new HRA dependency analysis process is proposed to reflect HFEs dependency analysis results into the cutsets and to reduce quantification resources once the determination of the level of depdency is determined. Ths steps are as follows.

(Step 1) Generate mapping table that each HFEs combination corresponds to an combined HFE using the dependency analysis result.

(Step 2) Generate mapping table that each original HFE has logical sum of the combined HFEs including the original HFE.

(Step 3) Modify the PSA model with the mapping table in Step 2 above.

(Step 4) Quantify the modified model and delete non-sense cutsets with more than or equal to 2 combined HFEs. Subsume the cutsets.

4. Application of the New HRA dependency analysis process

4.1 Model Description

The PSA model for the application of the new HRA dependency analysis process is as shown on Fig. I and Table I.

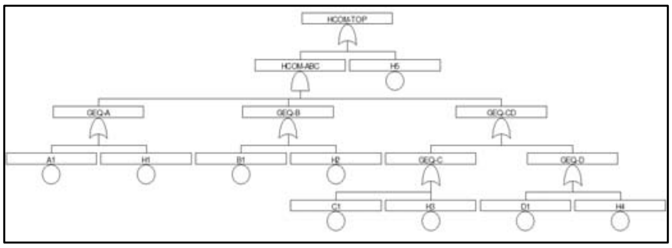

Fig. I. Example PSA model for application

Table I: Basic Event Information for the model

BE ID	Probability	Remark
A1	1.00E-02	Component Failure Event
B1	1.00E-02	Component Failure Event
C1	1.00E-02	Component Failure Event
D1	1.00E-02	Component Failure Event
H1	1.00E-03	Human Failure Event
H2	1.00E-03	Human Failure Event
H3	1.00E-03	Human Failure Event
H4	1.00E-03	Human Failure Event
H5	1.00E-03	Human Failure Event

4.2 HRA Dependency Analysis Process application with current practice

HFEs combinations identification result by fault tree quantification with each HFE probability set to 1.0 is as shown on Fig. II.

Fig. II. HFEs Combinations Indentificatio Result

Index	Prob	Event1	Event2	Event3
001	1.000000E+00	H5		
002	1.000000E+00	H1	H2	H4
003	1.000000E+00	H1	H2	H3
004	1.000000E-02	B1	H1	H4
005	1.000000E-02	C1	H1	H2
006	1.000000E-02	D1	H1	H2
007	1.000000E-02	A1	H2	H4
008	1.000000E-02	A1	H2	H3
009	1.000000E-02	B1	H1	H3
010	1.000000E-04	B1	D1	H1
011	1.000000E-04	A1	D1	H2
012	1.000000E-04	B1	C1	H1
013	1.000000E-04	A1	B1	H4
014	1.000000E-04	A1	B1	H3
015	1.000000E-04	A1	C1	H2
016	1.000000E-06	A1	B1	D1
017	1.000000E-06	A1	B1	C1

HFEs dependency analysis results using the HFEs combinations identified is as follows.

H1 * H2 = H1 * H2-HD
H1 * H3 = H1 * H3
H2 * H3 = H2 * H3-HD
H2 * H4 = H2 * H4-HD
H1 * H2 * H3 = H1 * H2-HD * H3-HD
H1 * H2 * H4 = H1 * H2-HD * H4-HD

Where, H2-HD means H2 has the high dependency on the preceding HFE(s) failure. Same as H3-HD and H4-HD.

The result for post processing to reflect HFEs dependency analysis result and to apply truncation limit of 1.E-7 is shown on Fig. III.

Index	Prob	Event1	Event2	Event3
001	1.000000E-03	H5		
002	**2.505003E-04**	H1	**H2-HD**	**H3-HD**
003	**2.505003E-04**	H1	**H2-HD**	**H4-HD**
004	**5.005000E-06**	A1	H2	**H4-HD**
005	**5.005000E-06**	A1	H2	**H3-HD**
006	**5.005000E-06**	C1	H1	**H2-HD**
007	**5.005000E-06**	D1	H1	**H2-HD**
008	9.999999E-07	A1	B1	D1
009	9.999999E-07	A1	B1	C1
010	1.000000E-07	A1	B1	H3
011	1.000000E-07	A1	C1	H2
012	1.000000E-07	A1	D1	H2
013	1.000000E-07	B1	D1	H1
014	1.000000E-07	A1	B1	H4
015	1.000000E-07	B1	C1	H1

Fig. III. Results with HRA dependency reflection

4.3 HRA Dependency Analysis Process application with New practice

HFEs combinations identification result by fault tree quantification with each HFEs combination probability set to the highest probability of an HFE in the combination is shown on the Fig. IV.

Index	Prob	Event1	Event2	Event3
001	1.000000E-03	H5		
002	1.000000E-06	A1	B1	C1
003	1.000000E-06	A1	B1	D1
004	1.000000E-07	A1	B1	H4
005	1.000000E-07	A1	C1	H2
006	1.000000E-07	B1	C1	H1
007	1.000000E-07	A1	B1	H3
008	1.000000E-07	B1	D1	H1
009	1.000000E-07	A1	D1	H2
010	1.000000E-08	D1	H1	H2
011	1.000000E-08	B1	H1	H3
012	1.000000E-08	A1	H2	H3
013	1.000000E-08	A1	H2	H4
014	1.000000E-08	C1	H1	H2
015	1.000000E-08	B1	H1	H4
016	1.000000E-09	H1	H2	H3
017	1.000000E-09	H1	H2	H4

Fig. IV. HFEs Combinations Indentificatio Result

HRA dependency anslysis to determine the level of dependency is exactly the same as the one by current practice.

The mapping table for the (Step 1) of HRA dependency analysis results implementation is as shown on Table II.

Table II: Mapping table for HFEs combination to combined HFE

H1	Z1
H2	Z2
H3	Z3
H4	Z4
H5	Z5
H1*H2-HD	Z12
H1*H3	Z13
H1*H4	Z14
H2*H3-HD	Z23
H2*H4-HD	Z24
H1*H2-HD*H3-HD	Z123
H1*H2-HD*H4-HD	Z124

The mapping table for the (Step 2) of HRA dependency analysis results implementation is as shown in Eq. (2) below.

$$
\begin{aligned}
&H1=Z1+Z12+Z13+Z14+Z123+Z124\\
&H2=Z2+Z12+Z23+Z24+Z123+Z124\\
&H3=Z3+Z13+Z23+Z123\\
&H4=Z4+Z14+Z24+Z124\\
&H5=Z5
\end{aligned}
\tag{2}
$$

In (Step 3) of HRA dependency analysis results implementation, PSA model was modified with the Eq. (2) above.

The quantification results before deleting non-sense cutsets for (Step 4) of HRA dependency analysis results implementation is shown on Fig. V.

Index	Prob	Event1	Event2	Event3
001	1.000000E-03	Z5		
002	2.505000E-04	Z123		
003	2.505000E-04	Z124		
004	5.005000E-06	A1	Z23	
005	5.005000E-06	A1	Z24	
006	5.005000E-06	C1	Z12	
007	5.005000E-06	D1	Z12	
008	1.000000E-06	A1	B1	C1
009	1.000000E-06	A1	B1	D1
010	5.005001E-07	Z12	Z4	
011	5.005001E-07	Z1	Z23	
012	5.005001E-07	Z1	Z24	
013	5.005001E-07	Z12	Z3	
014	2.505003E-07	Z12	Z24	
015	2.505003E-07	Z12	Z23	
016	1.000000E-07	A1	B1	Z3
017	1.000000E-07	A1	D1	Z2
018	1.000000E-07	A1	C1	Z2
019	1.000000E-07	A1	B1	Z4
020	1.000000E-07	B1	D1	Z1
021	1.000000E-07	B1	C1	Z1
022	1.000000E-08	C1	Z1	Z2
023	1.000000E-08	B1	Z1	Z4
024	1.000000E-08	B1	Z1	Z3
025	1.000000E-08	A1	Z2	Z4
026	1.000000E-08	D1	Z1	Z2
027	1.000000E-08	A1	Z2	Z3
028	1.000000E-08	B1	Z14	
029	1.000000E-08	B1	Z13	
030	1.000000E-09	Z1	Z2	Z4
031	1.000000E-09	Z1	Z2	Z3
032	1.000000E-09	Z14	Z2	
033	1.000000E-09	Z13	Z2	
034	5.005000E-10	Z13	Z23	
035	5.005000E-10	Z12	Z13	
036	5.005000E-10	Z14	Z24	
037	5.005000E-10	Z12	Z14	
038	5.005000E-10	Z14	Z23	
039	5.005000E-10	Z13	Z24	

Fig. V. Quantification Results before Deleting Non-sense cutsets.

The quantification results after deleting non-sense cutsets and subsuming for (Step 4) of HRA dependency analysis results implementation is shown on Fig. VI.

Index	Prob	Event1	Event2	Event3
001	**1.000000E-03**	**H5**		
002	**2.505003E-04**	**H1**	**H2-HD**	**H3-HD**
003	**2.505003E-04**	**H1**	**H2-HD**	**H4-HD**
004	**5.005000E-06**	C1	**H1**	**H2-HD**
005	**5.005000E-06**	D1	**H1**	**H2-HD**
006	**5.005000E-06**	A1	**H2**	**H4-HD**
007	**5.005000E-06**	A1	**H2**	**H3-HD**
008	9.999999E-07	A1	B1	C1
009	9.999999E-07	A1	B1	D1
010	**1.000000E-07**	A1	D1	**H2**
011	**1.000000E-07**	A1	C1	**H2**
012	**1.000000E-07**	A1	B1	**H4**
013	**1.000000E-07**	A1	B1	**H3**
014	**1.000000E-07**	B1	D1	**H1**
015	**1.000000E-07**	B1	C1	**H1**

Fig. VI. Quantification Results after Deleting Nonsens cutsets, HFEs retrieval and subsuming.

As can be seen in the Step4, we can get exactly the same cutsets as the one from current practice. This means that once the HFEs combinations were identified and level of dependency were determined, the quantification of the PSA model can be performed in a very effective manner without cutset post processing because the non-sense cutsets deletion and subsuming can be performed by quantification engine or FTEX.

5. Conclusions

In this paper, a new HRA dependency analysis process was proposed which can get all HFEs combinations with the selected truncation limit. If we use the new HRA dependency analysis process, we can quantify in a more efficient manner once the level of dependency for the HFEs combinations was determined.

With the application of the new HRA dependency analysis process to an example PSA model, its appropriateness and exactness was confirmed.

Applications of the new HRA dependency analysis process for actual plant PSAs are suggested which will lead to the more accurate CDF calculation and efficient HRA dependency analysis.

REFERENCES

[1] SNL, NUREG/CR-1278, Handbook of Human Reliability Analysis with Emphasis on Nuclear Power Plant Applications, 1983.

[2] EPRI, FTREX 1.9 Software Manual, Product ID # 3002012968, 2018.