Integrated HRA Dependency Treatment in PSA

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Currently the implementation process of human reliability analysis (HRA) dependencies in a nuclear power plant (NPP) probabilistic safety assessment (PSA) is very time consuming involving both PSA and HRA engineers with a lot of manual work. We propose an integrated innovative method for dependency treatment, both with regard to HRA dependency identification and quantification. The main idea is that the PSA software will recognize the HFEs and automatically apply the conditional probabilities for the additional HFEs within an MCS, i.e. dependency adjustment, while in the process of model MCS generation. The dependency level between HFEs in each HFE combination is evaluated in the HRA software and conditional HEPs are generated. The PSA software should then be able to use the information from HRA software in the MCS generation and quantification.

We believe this approach can greatly improve the efficiency of the HRA dependency treatment in a PSA model. The integration between RiskSpectrum PSA and HRA software in the dependency analysis will also improve the quality of the model. An HRA analyst will have a better control of the combination identification, because this approach eliminates the risk of losing combinations when applying the cutoff. Exact quantification of dependencies during MCS generation gives more accurate results faster.

I. INTRODUCTION

Currently the whole HRA dependency treatment process, including dependency evaluation and implementation in the PSA model, is very time consuming. The whole process involves both PSA and HRA engineers using PSA and HRA software. The process requires a large amount of manual work and several rounds of model calculation for MCSs generation and quantification.

This paper describes the challenges in the current industry HRA dependency treatment and explains how the proposed new approach can effectively deal with these challenges. This approach is being implemented in RiskSpectrum PSA and HRA software.

This paper focuses on the process of implementation of HRA dependencies in a PSA model. The HRA side of the issue, i.e. how to evaluate the HRA dependency levels for an HFE combination, is not covered in this paper, but can be found in many HRA reports, e.g. the NPSAG HRA dependencies report, Ref. 1.

II. CURRENT HRA DEPENDENCY IMPLEMENTATION PROCESS

HRA dependency treatment process might be different for different types of HFEs (Category A, B or Category C). For example for type A HFEs, the dependencies between the events can be effectively identified in the analysis for the redundant trains within a safety function. For example for the HRA dependencies in Category C HFEs, the MCSs need to be checked, thus it is typically performed with the following main steps:

Firstly the HFE combinations need to be identified as completely as possible in the MCSs of a PSA model. To avoid too early truncation of the HFE combinations, all relevant HFEs need to be manually set with high HEP values (e.g. 0.9) in the PSA model during the MCS generation. Millions of MCSs might be generated from a plant PSA model and usually the setting of the Maximum number of MCSs will be reached and the truncation level will be increased during the calculation.

Depending on the number of HFEs and also how HFEs are positioned in the PSA model, the HEP values and truncation level applied in the PSA calculation need to be optimized to generate MCSs with multiple HFEs. The multiple HFEs contained in one MCS are grouped as a HFE combination. The PSA model might need to be iteratively quantified for a thorough HFE combination identification.

Secondly the dependency level between the HFEs in the combination needs to be evaluated. As there will be many HFE combinations, the risk significant HFE combinations should be treated and applied in the PSA. The evaluation of the HRA dependency levels for an HFE combination is not discussed in this paper. This needs to be performed by HRA engineers, with or without HRA software. The conditional HEPs can be derived from the dependency level of HFEs in the combination.

With the conditional HEPs available for HFEs in the HFE combinations, the PSA model needs to be recalculated and post-processing rules are typically defined and applied for these HFE important combinations. This is performed at the MCS level using PSA software. There needs to be a ‘complete’ MCS list available to implement the post-processing rules. The MCS list needs to be generated from the PSA model using the optimized HEPs (seed values) applied to the related HFEs so that the HFE combinations can be kept without early truncation. The seed values are usually much lower than the high HEP values used in the first step to improve the calculation efficiency in the MCS generation. A feasible approach for seed values can be found in Ref. 2.

III. AN INTEGRATED HRA DEPENDENCY TREATMENT PROCESS

To improve efficiency of the HRA dependency treatment, we propose a novel method for dependency treatment in RiskSpectrum software, both with regard to HRA dependency identification and quantification. The main idea is that the calculation engine will recognize the HFEs and automatically apply the conditional probabilities for the multiple HFEs within a MCS, i.e. dependency adjustment, while in the process of model MCS generation. The dependency level between HFEs in one HFE combination is analyzed in the HRA software and conditional HEPs are generated. The PSA software should then be able to use the information from the HRA software in the MCS generation and quantification.

The proposed integrated HRA dependency treatment process in RiskSpectrum is illustrated in Figure 1.

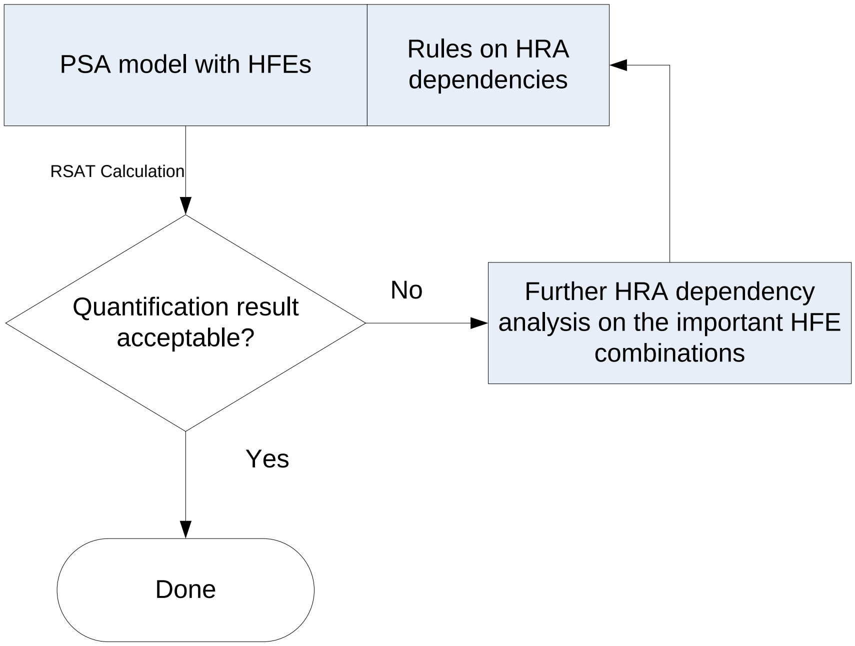


Fig. 1. An integrated HRA dependency treatment process.

The following steps are applied to perform the HRA dependency treatment:

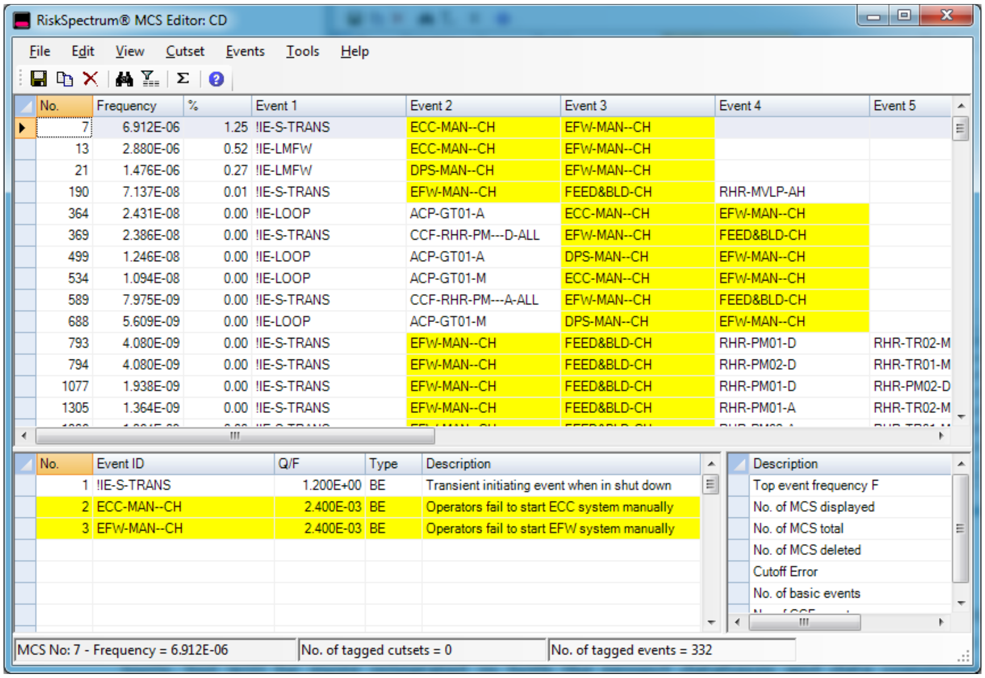
1. PSA model quantification with HRA dependency treatment. The quantification is performed considering the rules saved in the PSA database for HRA dependencies. The PSA engine is able to recognize the HFEs needed to consider the dependency. In the MCS generation and also quantification, the dependency rules will always be applied. There is no need to have the initial quantification which increases all HEPs to high values (e.g. 0.9) to avoid premature truncation of cutset with multiple HFEs. The HRA dependency rules become part of the PSA model information, instead of post-processing rules applied only on the generated MCSs. When there is no rule defined for a HFE combination, a default rule can be applied. The default rule is to make sure a conservative treatment for the multiple HFEs contained in one MCS. One example of the default rule is that only the HFE with the lowest HEP will keep its original HEP, all other HFEs will have HEP as 1, i.e. a complete dependency with the HFE.

2. The quantification results can be checked to see if the derived quantification is too conservative or not. The quantification results can be very conservative if the default rule is applied for the risk dominant MCSs containing multiple HFEs. In such a case, these important HFE combinations need to be further evaluated to derive a proper dependency level among them. The HFE combinations are identified from the MCSs in PSA software and their dependency levels are evaluated in the HRA software.

3. Since there will be a large number of MCSs containing multiple HFEs, it is possible to rank the MCSs and generate HRA dependency rules from the dependency analysis on the selected risk important MCSs. The rules will be added to the PSA model and applied in the future PSA model quantification. This step can be performed iteratively until all the important combinations have been analyzed and assigned with the proper dependency rules. For the risk insignificant combinations, the default rule will be applied.

III. EXISTING PSA SOFTWARE FEATURES FOR HRA DEPENDENCY

There are features available in the existing RiskSpectrum PSA software that can be used for HRA dependency treatment. Some of the widely used features include: (1) MCS editor, see figure 2, which is able to filter MCSs with two or more HFEs, (2) post-processing actions to apply the conditional HEPs for the dependent HFEs. An example action is to delete a HFE and add a new conditional HFE.



No.	Frequency	%	Event 1	Event 2	Event 3	Event 4	Event 5
7	6.912E-06	1.25	!IE-S-TRANS	ECC-MAN--CH	EFW-MAN--CH		
13	2.880E-06	0.52	!IE-LMFW	ECC-MAN--CH	EFW-MAN--CH		
21	1.476E-06	0.27	!IE-LMFW	DPS-MAN--CH	EFW-MAN--CH		
190	7.137E-08	0.01	!IE-S-TRANS	EFW-MAN--CH	FEED&BLD-CH	RHR-MVLP-AH	
364	2.431E-08	0.00	!IE-LOOP	ACP-GT01-A	ECC-MAN--CH	EFW-MAN--CH	
369	2.386E-08	0.00	!IE-S-TRANS	CCF-RHR-PM---D-ALL	EFW-MAN--CH	FEED&BLD-CH	
499	1.246E-08	0.00	!IE-LOOP	ACP-GT01-A	DPS-MAN--CH	EFW-MAN--CH	
534	1.094E-08	0.00	!IE-LOOP	ACP-GT01-M	ECC-MAN--CH	EFW-MAN--CH	
589	7.975E-09	0.00	!IE-S-TRANS	CCF-RHR-PM---A-ALL	EFW-MAN--CH	FEED&BLD-CH	
688	5.609E-09	0.00	!IE-LOOP	ACP-GT01-M	DPS-MAN--CH	EFW-MAN--CH	
793	4.080E-09	0.00	!IE-S-TRANS	EFW-MAN--CH	FEED&BLD-CH	RHR-PM01-D	RHR-TR02-M
794	4.080E-09	0.00	!IE-S-TRANS	EFW-MAN--CH	FEED&BLD-CH	RHR-PM02-D	RHR-TR01-M
1077	1.938E-09	0.00	!IE-S-TRANS	EFW-MAN--CH	FEED&BLD-CH	RHR-PM01-D	RHR-PM02-D
1305	1.364E-09	0.00	!IE-S-TRANS	EFW-MAN--CH	FEED&BLD-CH	RHR-PM01-A	RHR-TR02-M

No.	Event ID	Q/F	Type	Description
1	!IE-S-TRANS	1.200E+00	BE	Transient initiating event when in shut down
2	ECC-MAN--CH	2.400E-03	BE	Operators fail to start ECC system manually
3	EFW-MAN--CH	2.400E-03	BE	Operators fail to start EFW system manually

Description
Top event frequency F
No. of MCS displayed
No. of MCS total
No. of MCS deleted
Cutoff Error
No. of basic events

MCS No: 7 - Frequency = 6.912E-06
No. of tagged cutsets = 0
No. of tagged events = 332

Fig. 2. MCS Editor shows only MCSs with multiple HFEs

These features can be continuously used in the HRA dependency analysis. However for the proposed HRA dependency process, more functions will be added to RiskSpectrum PSA and the HRA software. The two tools will still remain as stand-alone tools, but will be more integrated in both the project databases and data communications to support improved HRA dependency treatment. HRA dependency level evaluation will be included in the HRA software.

IV. MODEL QUANTIFICATION ISSUES RELATED TO THE HRA DEPENDENCY

IV.A. Quantification Issues in the Current Practices

The quantification of the HRA dependency in a PSA model is a complex issue. Current industry practices focus on the adjustment of the probabilities of the dependent events in the same MCS. There are different options in the implementation. These practices produce a rough estimation, not the correct result from the mathematic point of view.

To illustrate quantification issues for HFE dependencies, let us study the following example. We assume there is a system with two safety barriers, each of them requiring a human action. The system fails if both barriers fail:

- Barrier 1: HFE A represents the operator failing to start a cooling pump. Basic event C represents the pump failure in the Subsystem 1.
- Barrier 2: HFE B represents the operator failing to open a release valve and start the system self-circulation. Basic event D represents the valve failure in the Subsystem 2.

The formula for a failure of the whole system is: (A+C)*(B+D).

The set of minimal cutsets (MCSs) for the system failure is:

MCS1: A, D
MCS2: C, D
MCS3: B, C
MCS4: A, B

Let us assume that P(A) = 1E-3, P(B) = 2E-3, P(C) = 3E-3 and P(D) = 4E-3. Since it is the same operator who performs the action A first and then the action B, the HRA analyst defines these two actions as dependent. Typically a positive dependence is assumed for the failures, which means the operator will more likely fail B action after he fails A. This can be described as $P(B|A) > P(B)$. Based on the dependency level (from zero dependency to full dependency), the conditional probability $P(B|A)$ will be in the rage of [P(B), 1].

It is very clear that we need to use the conditional probability when we calculate the probability of MCS4 (A, B). The probability P(MCS4) i.e. P(A and B) would be $P(A) * P(B|A)$ instead of $P(A) * P(B)$. The current industry practices focus on this adjustment and typically use one of the three following options in the treatment of MCS4:

- Option 1: keep A, B and add a multiplier M whose value is larger than 1
- Option 2: Keep A, replace B with a new event, let's say B1 whose probability is $P(B|A)$, adjusted from $P(B)$ according to the dependency level
- Option 3: Replace A and B with a new combination event (AB) whose probability is $P(A) * P(B|A)$

For all three options, after treatment, all the events i.e. A, B, B1, (AB) are then treated as standard basic events in the PSA model, i.e. independent. In the quantification of the total system failure from the above 4 MCSs, we need to calculate the individual MCS probability for the first order approximation and Min-cut upper bound approximation, as well as the intersections among the MCSs for the higher order approximations.

- First order approximation = P(MCS1) + P(MCS2) + P(MCS3) + P(MCS4)

- Second order approximation = First order approximation – P(MCS1 and MCS2) – P(MCS1 and MCS3) – P (MCS1 and MCS4) –P (MCS2 and MCS3) – P (MCS2 and MCS4) – P(MCS3 and MCS4).

- Third order approximation = Second order approximation + P(MCS1 and MCS2 and MCS3) + P(MCS1 and MCS2 and MCS4) + P(MCS2 and MCS3 and MCS4)

- Fourth order approximation = Third order approximation – P(MCS1 and MCS2 and MCS3 and MCS4)

Note that for the second order approximation, A and B will also show in the union of MCS1 and MCS3, in the union of MCS1 and MCS4, in the union of MCS2 and MCS4, in the union of MCS3 and MCS4. For the third and the fourth order approximation, A and B occur in all unions. The fourth order approximation is also the exact value of the MCS list. Similarly, we need to consider quantification of arbitrary combinations of failures and successes of basic events when building and quantifying a BDD built from the MCS list.

For the higher order approximation, it is clear that HFE event A and B will appear together in the unions (characterizing the fact that events from both of these cutsets occur during an accident) and thus dependency exists among the unions of the MCSs. This is not systematically considered in any PSA quantification yet. The current industry practice does not fully account for this part. Note that the different options in the treatment of MCS4 will produce different quantification results.

We take option 2 as an example, i.e. replace B with B1 in the MCS4. B1 is then considered as a new standard basic event in the PSA model and let us assume that P(B1) = 0.14. Thus the union of MCS3 and MCS4 will be (A, B, B1 and C) from option 2, instead of (A, B1 and C) as expected/wanted. Also union of MCS1 and MCS3 will be (A, B, C and D) from option 2, instead of (A, B1, C, D). So we can see that in some unions B is not replaced with B1 when A and B occur together, and in some unions, both probabilities of B and B1 are counted. Table I shows the hand quantifications from option 2 as compared with the expected results.

TABLE I. Quantification from Option 2

	Option 2 results	Results from correct quantification
First order approximation	0.000162	0.000162
Second order approximation	0.000161401	0.000160981
Third order approximation	0.000161403	0.000160986
Forth order approximation	0.000161403	0.000160984

In general all three options change the logical representation of the system by adding new events or replacing current events with new ones. After this, the MCS list representation of the system is quantified by standard algorithms.

IV.B. Proposed New Quantification

Different quantification options used in the industry practice give different results. This shows that there is no clear mathematical meaning – *semantics* – of HRA dependencies in PSA models, defining what the correct value should be, Ref. 3.

To cope with the problem caused by adding new events or replacing current events with new ones, we would like to propose a new approach which keeps the original logical representation of the system, i.e. does not change the structure of the MCS list, but adapts the quantification algorithms to estimate the failure probabilities of the dependent events within one MCS as well as in the unions of the different MCSs. This will systematically produce a correct result considering the dependency in event A and B in MCSs and their unions.

In order to define clear semantics of a fault tree with dependencies between HFEs, we need to define probabilities of all combinations of failure/success of events A and B, so called *minterms*. The sum of probabilities of minterms that fail the top gate gives the exact failure probability. To achieve this, we need to define probabilities of dependent events in all failure/success combinations of dependent events and events on which they depend. The remaining events are treated as independent, i.e., the probability of their failure/success is multiplied into the minterm probability.

Clearly, P(A, B) = $P(A) * P(B|A)$ where P(B|A) is the value defined by the dependency analysis in HRA. The remaining combinations depend on how we define the dependent probability P(B|A'). We would assume P(B) is the probability of the operator failure B regardless of whether A has happened or not and then we calculate P(B|A') from P(B) and P(B|A).

We need to quantify the MCS list so that we obtain the exact system failure probability or its over-approximation (such as Rare Event Approximation or Min Cut Upper Bound) or its under-approximation (e.g., 2nd order approximation). For example, we need to define how we quantify cutsets containing both A and B, cutsets containing only A, cutsets containing only B and how we quantify the probability that two or more cutsets occur at the same time.

The calculation would work like this:

- quantify cutsets containing A and B (and possibly other events $C_1 \ldots C_n$) by $P(A)*P(B|A)*\prod P(C_i)$
- quantify cutsets containing only B (and possibly other events $C_1 \ldots C_n$) by $P(B)*\prod P(C_i)$
- quantify cutsets containing only A (and possibly other events $C_1 \ldots C_n$) by $P(A)*\prod P(C_i)$
- calculate the probability that two or more cutsets occur at the same time as the probability of the cutset created as a union of these cutsets. This means that if one cutset contains only A and the other one contains only B then the probability that they occur at the same time takes the conditional failure probability P(B|A) of B into account.

IV. CONCLUSIONS AND FUTURE WORK

We believe the proposed integrated HRA dependency treatment process can greatly improve the efficiency of the current HRA dependency treatment in PSA. Compared with the traditional way, it has the following advantages:

1. There will be less calculation iterations for the model in the MCSs identification and quantification. There is no need to have the initial quantification process which manually set HFEs to high values to generate the MCSs with multiple HFEs.

2. The HRA dependency rules are applied while in the MCS generation as well as quantification. There is no need to apply the rules as post-processing actions in the generated MCSs.

3. The quantification issues caused by the current practices would be eliminated by the proposed quantification approach. This would improve the accuracy of the model calculation.

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