

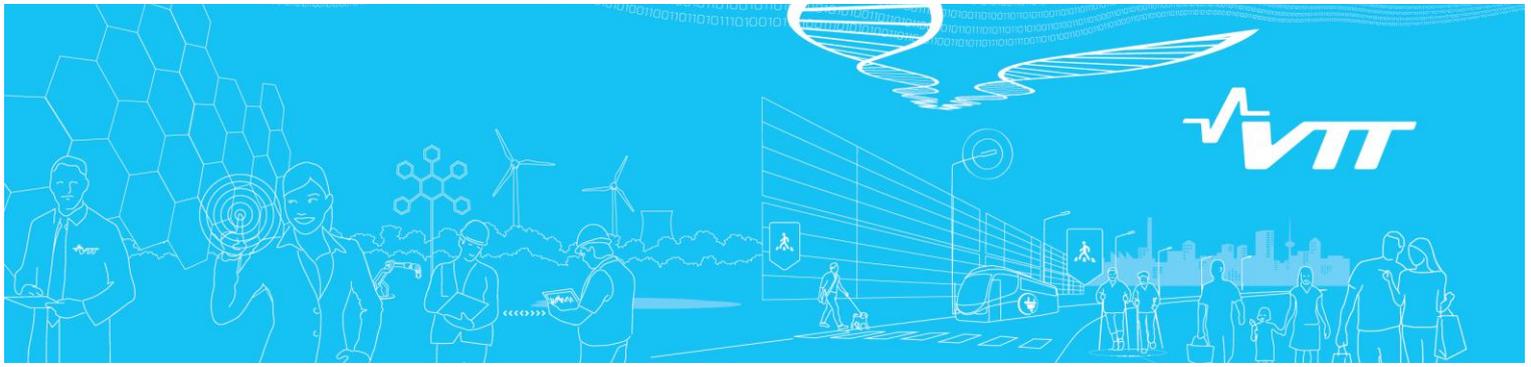
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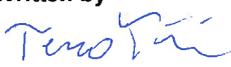
RESEARCH REPORT

VTT-R-03893-16

FinPSA – User guide – Tight integration of PRA levels 1 and 2

Authors: Tero Tyrväinen

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<p>FinPSA is a software tool for full-scope probabilistic risk assessment (PRA). FinPSA contains tool support for PRA levels 1 and 2. Level 1 PRA analyses accident sequences leading to a core damage, and level 2 PRA analyses the progression of severe accidents after the core damage. PRA is most accurate when dependencies between levels 1 and 2 are modelled, and all the relevant information is passed from level 1 to level 2. This document is a user guide that presents how the features related to the tight integration of levels 1 and 2 work in FinPSA. The document covers both tight integration modelling and the corresponding presentation of results.</p>		
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Abbreviations

CET	Containment event tree
ECC	Emergency core cooling
PDS	Plant damage state
PRA	Probabilistic risk assessment

1. Introduction

FinPSA is a software tool for full-scope probabilistic risk assessment (PRA) [1]. FinPSA contains tool support for PRA levels 1 and 2. Level 1 PRA analyses accident sequences leading to a core damage [2], and level 2 PRA analyses the progression of severe accidents after the core damage [3]. Figure 1 presents different phases of FinPSA analysis including both levels 1 and 2. The purpose of this document is to guide FinPSA users on tight integration of levels 1 and 2.

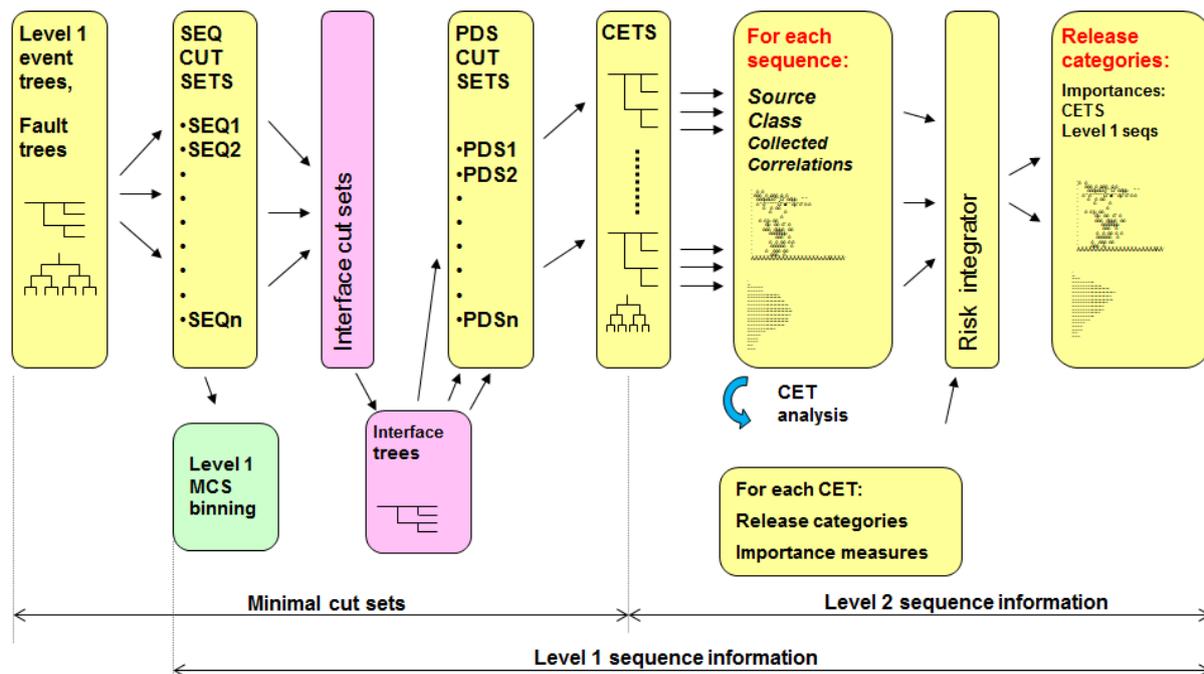


Figure 1: FinPSA analysis phases.

PRA is most accurate when dependencies between levels 1 and 2 are modelled, and all the relevant information is passed from level 1 to level 2. However, in FinPSA, analyses of levels 1 and 2 are performed using different methods. Level 1 of FinPSA uses standard event tree-fault tree approach and produces minimal cut sets as results [4]. Level 2 of FinPSA uses dynamic containment event trees combined with script files written in CETL programming language [1]. FinPSA is briefly presented in Section 2. Section 3 presents how level 1 information can be incorporated and utilised in level 2 models. In Section 4, it is shown how accident sequences and basic events of level 1 are seen in level 2 results. Appendix presents a summary table on the new CETL functions, routines and variable types.

2. FinPSA

2.1 Level 1

FinPSA level 1 modelling is based on fault trees that are linked to event trees [2]. In fault trees, it is modelled what combinations of basic events can cause the failures of different safety functions and systems, and other events. In event trees, accident sequences are modelled starting from an initiating event and ending to a core damage category which is determined by failures of specified safety systems. From this model, FinPSA calculates minimal cut sets (minimal combinations of basic events that cause the consequence) for different consequences, e.g. core damage categories.

To integrate level 1 results to level 2 analysis, FinPSA offers interface trees which are used to categorise level 1 results to plant damage states (PDS). The categorisation is performed to link accident sequences leading to a similar plant state to the same PDS. A PDS is associated with a containment event tree on level 2. For each PDS, minimal cut sets are calculated, and from the minimal cut sets, the frequency of the PDS can be computed. For the frequency, uncertainty distribution can be calculated if uncertainty distributions have been specified for basic events. Each minimal cut set of a PDS is also associated with an accident sequence represented by an event tree and interface tree identifier so that its origin can be traced back.

2.2 Level 2

The level 2 method implemented in FinPSA is based on dynamic containment event trees (CET) and CETL programming language [1, 5]. The CETL language is used to define functions to calculate conditional probabilities of CET branches, timings of the accident progression and amounts of releases. The modelling approach is very flexible and it enables parametric models that can account dynamic dependencies and phenomena. It is possible to define uncertainty distributions for the variables and perform Monte Carlo simulations. Finally, simulation results from different sequences and CETs are integrated and statistical analyses are performed to calculate uncertainty distributions and statistical parameters for the releases.

The frequency of a plant damage state can be calculated in the init routine of the initial section with line

```
BinFreq = PDSCUTSFREQ()
```

If uncertainties have been modelled in level 1, PDSCUTSFREQ performs uncertainty analysis on level 1 results and draws a value from the resulting distribution on each simulation cycle.

3. Level 1 information in level 2 computation

3.1 Accident sequences

There are typically many level 1 accident sequences leading to the same PDS. Different accident sequences can affect later severe accident progression differently. Therefore, it is possible to categorise accident sequences inside a PDS in the corresponding CET model. This can be done in SC_DEF routine in FinPSA level 2. In this routine, categorisation rules are defined for accident sequences based on level 1 event tree sections (see example coming later). Then, probabilities of these categories can be calculated later in the CET model.

The basis for accident sequence categorisation is the descriptions of event tree sections. In Figure 2, section descriptions are T, C, Q, U, X, V, W1 and W3. Interface trees include similar section descriptions. Each accident sequence can be represented using the descriptions of those sections that correspond to the system failures in the accident sequence. For example, the representation of sequence 10 is T Q.

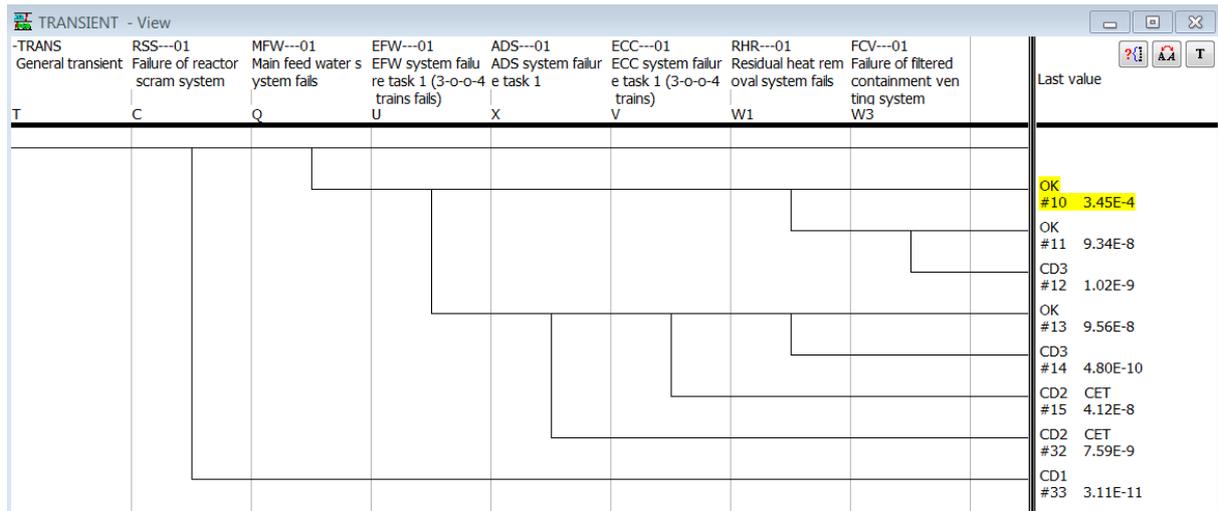


Figure 2: Level 1 event tree.

In initial section of a containment event tree, it is possible to define SC_DEF routine that categorises level 1 accident sequences. The categorisation can be performed using the Boolean operations that are available in CETL language, including OR, AND, XOR and NOT. An example of this is presented on the following CETL code lines.

```
sc_id ECCfail, ECCrec

routine sc_def
  ECCfail = ('V' or 'X' or 'W1') and 'Q' and 'U'
  ECCrec = not ECCfail
return
```

These code lines define two SC_IDs which are level 1 sequence categories. ECCfail represents those sequences where emergency core cooling (ECC) system cannot be recovered, and ECCrec represents those sequences where ECC system can be recovered. From the event tree of Figure 2, the sequences of ECCfail would be 14, 15 and 32, and the sequences of ECCrec would be 10-13 and 33 (assuming that they lead to a PDS). However, a real SC_DEF example would consider interface tree sequences in combination with level 1 event tree sequences. SC_DEF routine is executed once always before simulations.

If SC_DEF routine is used, a list of level 1 sequences (which are combinations of event tree and interface tree sequences) is carried in the level 2 calculations. In the beginning, the list includes all the level 1 sequences that lead to the PDS of the CET, but the list can be reduced. SC_IDs can be used in calculations by calling SC_INCL function. The function calculates and returns the portion of the sequences of the chosen SC_ID in the sequence list based on minimal cut sets and their frequencies. The function also reduces the sequence list to include only sequences of the chosen SC_ID in the calculations of the subsequent parts of the CET. An example of the use of SC_INCL function is presented on the following CETL code lines.

```
$ ECCS recovery possible
function real RP
  p = sc_incl(ECCrec)
return p
```

\$-----

```

$ ECCS recovery not possible
function nil NRP
  x = sc_incl(ECCfail)
return nil

```

Function RP returns the probability if the ECC system recovery is possible which is the probability of SC_ID ECCrec, which in other words is the probability of those accident sequences where the recovery is possible in this PDS. The list of level 1 sequences is also reduced so that it includes only the sequences of ECCrec in the later parts of the CET (in sequences 1-8 in Figure 3). In function RNP, SC_INCL function is also used with SC_ID ECCfail. The probability of ECCfail is not used because RNP must return nil, but SC_INCL reduces the sequence list to include only the sequences of ECCfail in the later parts of the CET (in sequences 9-11 in Figure 3). If the probability of some other SC_ID is calculated in the CET later, it is done based on the reduced list. At the end points of the CET, the contributions of level 1 sequences to the level 2 results (see Section 4.1) are also calculated based on the reduced list.

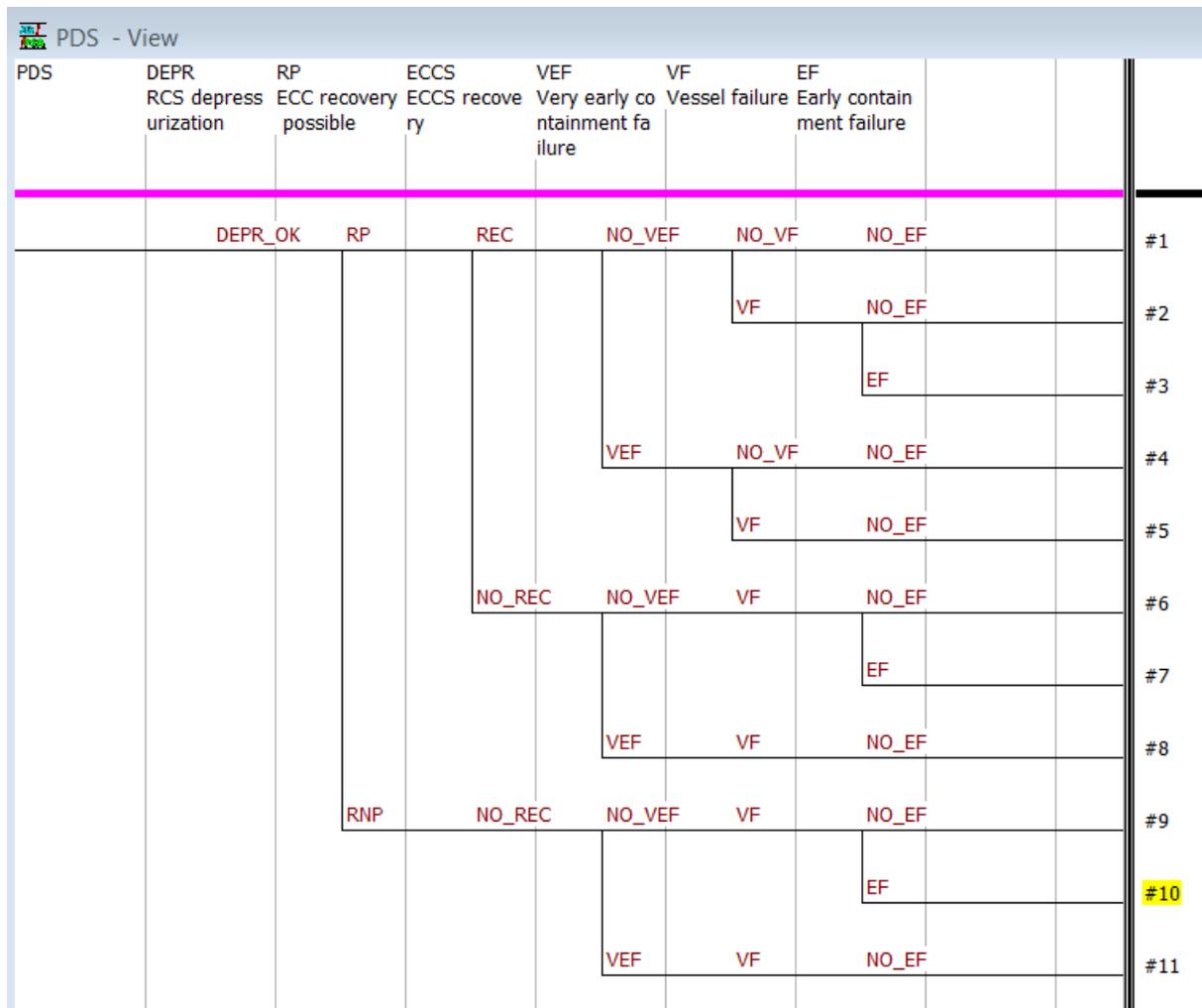


Figure 3: Containment event tree.

In the example CET of Figure 3, it is first asked in section RP if the ECC system recovery is possible based on level 1 results. If the recovery is possible, the success probability of the recovery is then calculated in section ECCS, because the recovery could fail even if it is possible based on level 1 results. In principle, similar modelling could be performed in one section only. However, two separate sections (or three branches in one section) are needed so that level 1 sequences are divided to the level 2 branches correctly.

Function SC_PROB calculates the probability of a SC_ID in the same way as SC_INCL, but it does not reduce the level 1 sequence list.

3.2 Basic events

It is possible to calculate the conditional probability of a basic event in level 2 using BE_FV function. This conditional probability is the Fussell-Vesely [6] of the basic event in the level 1 sequence list, i.e. the portion of the minimal cut sets that include the basic event in the minimal cut set list where minimal cut sets from different level 1 sequences have been combined. The level 1 sequence list is the same that was discussed in the previous section. The name of the basic event is given as an argument of the function, e.g. BE_FV('ECC10PM001_A'). It is also possible to give two basic events as arguments, in which case function BE_FV2 should be called, e.g. BE_FV2('ECC10PM001_A', 'ECC10VM001_A'). In that case, only those minimal cut sets that include both specified basic events are taken into account.

4. Level 1 events in level 2 results

4.1 Level 1 sequences

FinPSA calculates the contributions of level 1 sequences to

- frequency
- values of source variables

in each release category and level 2 sequence. They appear in regular level 2 frequency and source variable results after percentile values. The contributions are mean values calculated over simulation cycles.

The contribution of level 1 sequence i to the frequency of level 2 sequence j is

$$C^f(i, j) = \frac{\sum_{k=1}^n F_{i,j}(k) \cdot f_j(k)}{\sum_{k=1}^n f_j(k)},$$

where n is the number of simulations, $F_{i,j}(k)$ is the fraction of level 1 sequence i in level 2 sequence j in simulation cycle k and $f_j(k)$ is the frequency of level 2 sequence j in simulation cycle k .

The contribution of level 1 sequence i to the source variable v in level 2 sequence j is

$$C^v(i, j) = \frac{\sum_{k=1}^n F_{i,j}(k) \cdot f_j(k) \cdot v_j(k)}{\sum_{k=1}^n f_j(k) \cdot v_j(k)},$$

where $v_j(k)$ is the value of variable v in level 2 sequence j in simulation cycle k .

The contribution of level 1 sequence i to the frequency of release category r is

$$C^f(i, r) = \frac{\sum_{k=1}^n \sum_{j \in r(k)} F_{i,j}(k) \cdot f_j(k)}{\sum_{k=1}^n \sum_{j \in r(k)} f_j(k)},$$

where $r(k)$ is the set of level 2 sequences leading to release category r in simulation cycle k .

The contribution of level 1 sequence i to the source variable v in release category r is

$$C^v(i, r) = \frac{\sum_{k=1}^n \sum_{j \in r(k)} F_{i,j}(k) \cdot f_j(k) \cdot v_j(k)}{\sum_{k=1}^n \sum_{j \in r(k)} f_j(k) \cdot v_j(k)}$$

Level 1 sequence contributions are presented in the results in the following form.

Level 1 sequence importances > 1E-4

Num	Seq.	%	Description
1	3E	41.76	F W1 FG
2	6A	34.11	O Q W1 AW
3	18E	24.13	S UL TS

Only sequence contributions above 1E-4 are presented. This limit value 1E-4 can be changed by the user in project settings. Table 1 describes the meanings of the headers of the sequence contributions list.

Table 1: The headers of the sequence contributions list.

Header	Description
Num	The order number of the sequence. The most important sequence has 1, the second most import sequence has 2, etc.
Seq.	The number of the level 1 sequence and the letter of the interface tree sequence.
%	The contribution of the sequence.
Description	The representation of the sequence in the form of the event tree section descriptions.

4.2 Level 1 basic events

FinPSA calculates the contributions of level 1 basic events (and initiating events) to

- frequency
- values of source variables

in each release category and level 2 sequence. Basic event contributions are calculated based on level 1 sequence contributions. The contribution of a basic event is the sum of its Fussell-Vesely [6] values in different sequences weighted by the corresponding sequence contributions:

$$C(BE) = \sum_{i \in S} FV(BE|seq = i) \cdot C(i),$$

where $C(BE)$ is the contribution of the basic event, S is the set of level 1 sequences, $FV(BE|seq = i)$ is the Fussell-Vesely of the basic event in level 1 sequence i and $C(i)$ is the contribution of level 1 sequence i .

Basic event contributions are included in the regular level 2 frequency and source variable results when the Basic event contributions check box is checked in CET results window (Figure 4) or Risk integrator window (Figure 5). The basic event contributions appear after the level 1 sequence contributions. Level 1 basic event contributions are presented in the results in the following form.

Level 1 basic event importances > 1E-4

Num	Name	%	Comment
1	ECCPM01A-ABCD	32.05	4x CCF ECCS pump fails
2	ECCVM01A-ABCD	22.25	4x CCF ECCS valve fails
3	ECCTR01M	1.21	ECCS train under maintenance

Only basic event contributions above 1E-4 are presented. This limit value 1E-4 can be changed by the user in project settings.

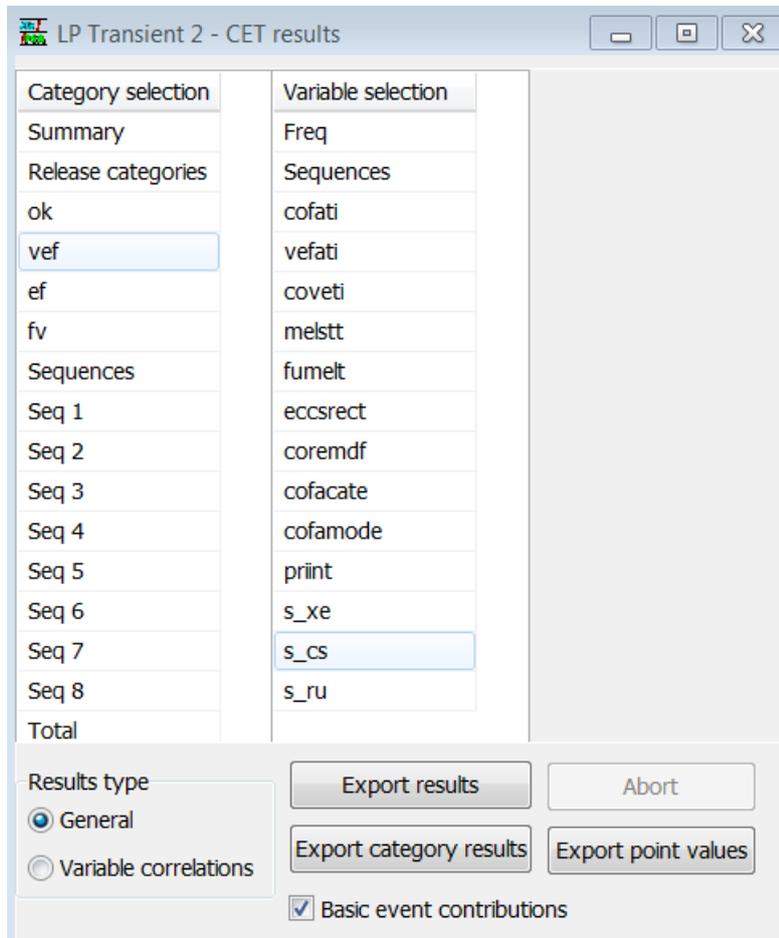
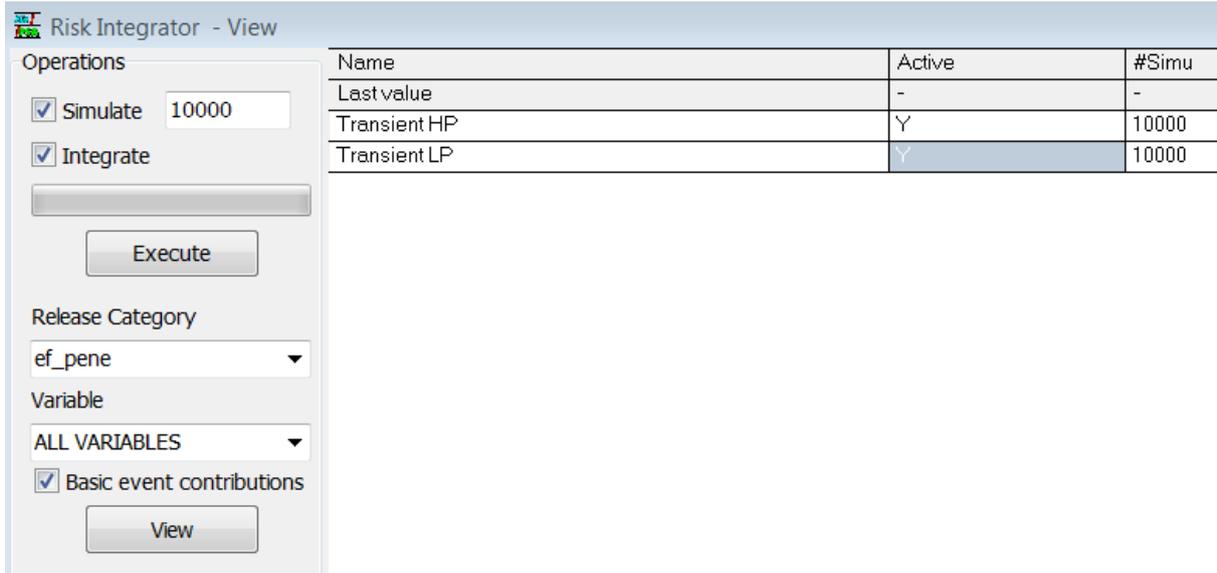


Figure 4: CET results window.



Name	Active	#Simu
Last value	-	-
Transient HP	Y	10000
Transient LP	Y	10000

Figure 5: Risk integrator.

5. Conclusions

This document presented how information of level 1 accident sequences can be used in level 2 modelling. It is possible to calculate probabilities of some level 2 actions, such as cooling system recovery, based on probabilities of level 1 sequences and basic events. Contributions of level 1 sequences and basic events to level 2 results can also be calculated in FinPSA.

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Appendix

Table 2: CETL functions, routines and variable types related to the tight integration.

Function/routine/type	Description
BE_FV	Function calculates conditional probability of a basic event in level 2 based on the level 1 sequence list.
BE_FV2	Function calculates conditional probability of a pair of basic events in level 2 based on the level 1 sequence list. In the computation, only minimal cut sets containing both basic events are taken into account.
SC_DEF	Routine contains categorization rules for level 1 sequences. SC_ID items are defined in this routine.
SC_ID	A sequence category is defined based on sequence descriptions of event trees and interface trees. It is defined in SC_DEF routine.
SC_INCL	Function calculates and returns the portion of the sequences of the chosen SC_ID in the sequence list based on minimal cut sets and their frequencies. The function also reduces the sequence list to include only sequences of the chosen SC_ID in the calculations of the subsequent parts of the CET.
SC_PROB	Function calculates and returns the portion of the sequences of the chosen SC_ID in the sequence list based on minimal cut sets and their frequencies.