Human Reliability Dependency Analysis and Model Integration Process

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Abstract: The purpose of this paper is to describe the process for integrating *HRA Calculator*® dependency analysis results into a *CAFTA* cutset model. Fundamental to this process is that dependencies between human failure events (HFEs) need to be addressed before cutsets are truncated to prevent inappropriate truncation of cutsets containing dependent HFEs. To prevent truncation, human error probabilities (HEPs) need to be set to high values before solving the fault tree. For a model with more than 100 post-initiator HFEs, this can be a formidable challenge due to the exponential nature of the problem – current PC hardware and software limits can be challenged. To assist in this process, the *HRA Calculator Helper* software tools for optimizing HEP values to prevent inappropriate truncation from a cutset solution and for generating cutset recovery rules files to implement dependent joint HEPs in the cutsets are discussed.

Keywords: HRA Calculator, Dependency Analysis, CAFTA, Quantification

1. BACKGROUND

Probabilistic risk assessment (PRA) is performed in the USA in accordance with the ASME/ANS PRA Standard [1], hereafter referred to as the "*PRA Standard*", as endorsed by Regulatory Guide 1.200 [2]. All nuclear power plants are required to have PRAs and they are typically applied in risk management. EPRI has developed several software programs to build PRA models that are in widespread use in the USA and also in a number of international utilities. The suite of programs collectively known as the *Risk and Reliability (R&R) Workstation* includes software like *CAFTA* [3] and *PRAQuant* (batch processor for quantification) [4]. EPRI also developed the *HRA Calculator*® [5] which is a software implementation of various human reliability (HRA) methods [6, 7 and 8]. The *HRA Calculator* has a dependency analysis module that can import cutsets, identify combinations of human failure events (HFEs), apply systematic dependency rules and generate joint human error probabilities (HEPs) that need to be applied to the cutsets via post-processing as part of the PRA quantification process. This requires interfacing between the *HRA Calculator* and *CAFTA.* To facilitate this process, a software package called *HRACalculator Helper* has been developed for distribution with the *HRA Calculator*. This package contains two utilities; one for generating a *CAFTA QRecover* recovery rules file from *HRA Calculator* output, and one for generating HEP seed values used to quantify a model before applying the recovery rules file.

2. INTRODUCTION

The purpose of HRA dependency analysis as part of PRA is to identify combinations of HFEs in cutsets and to evaluate them for possible dependencies. The fundamental concern is that HFEs may not be statistically independent, which can lead to underestimation of risk metrics when using cutset methodology. The *PRA Standard* has specific high level requirements "QU-C1" to identify combinations of HFEs and "QU-C2" to evaluate them for dependencies. It is very important to note that the dependency analysis needs to be accomplished *before* cutsets are truncated. Performing a dependency analysis after cutset truncation leaves open the concern about inappropriate truncation due to joint HEPs that may be unjustifiably low. This paper describes the iterative processes developed to integrate dependency analysis results obtained from the *HRA Calculator* into a *CAFTA* model.

3. MODEL INTEGRATION PROCESS

3.1. Identification of HFE Combinations

The basic approach to avoid inappropriate truncation is to set all the post-initiator HEPs to 1.0 then re-generate the cutsets to force retention of cutsets that would normally truncate out due to low joint HEPs based on independent HEP values. If the model can solve with HEPs set to 1.0 at the same truncation level where the nominal model is convergent (less than 5% added to total risk metric at next lower order truncation level per *PRA Standard* supporting requirement “QU-B3”), all HFE combinations can be identified. However, in practice, a model with more than 100 or so HFEs may not solve with HEPs set to 1.0, given current computer hardware and software limitations. This requires both lowering the HEPs as well as truncation levels iteratively until a practical cutset solution can be obtained to start the identification process with.

The identification process is illustrated in Figure 1 below. The HEPs are initially set to 1.0 (using a flag file) in Step 1.1. The truncation level is set to a relative high value e.g. 1E-06 in Step 1.2. Generation of cutsets is then attempted at successively lower truncation levels using a *PRAQuant* batch processing file. If cutsets can be generated at the truncation level where the cutsets normally converge e.g. 1E-12, all cutsets that had previously truncated out due to low joint HEPs are retained in the solution for dependency analysis. However, if cutsets cannot be generated at this truncation level, the HEPs are decreased by 0.1 (as long as HEPs are not decreased to less than their independent values) and the next iteration is started through the cutset generation process. These iterations are continued until a cutset solution at 1E-12 is found or until the HEP value reaches 0.1. HEP values less than 0.1 are not recommended for identification purposes as too few combinations may be identified resulting in “unanalyzed” combinations appearing in the cutsets after seed values are applied, which delays convergence and/or may be unacceptable to the results, as joint HEPs for unanalyzed combinations are set to 1.0 in this approach.

In practice, the identification process can result in anything from several hundred thousand to a few million cutsets for a typical internal events PRA core damage frequency (CDF) model. The number of cutsets generated when HEPs are set to 1.0 is an exponential function of the number of HFEs in the model. Typical results for a “well behaved” CDF model with 89 HFEs are shown in Table 1, yielding 1,584,636 cutsets at 1E-12. In this case it was possible to find a solution at 1E-12 with all HEPs set to 1.0 by running a single top model. Typical results for a CDF model with 160 HFEs are shown in Table 2. In this case, a solution could not be obtained at 1E-12 with HEPs set to 1.0, which required lowering the HEPs as well as truncation level, yielding 1,317,312 cutsets at 1E-11 with HEPs at 0.1. These numbers of cutsets are handled quite adequately by *CAFTA* Version 5.4 and the *HRA Calculator* Version 5.

The cutsets are imported into the *HRA Calculator* in Step 1.3. For the examples above, 1292 HFE combinations were identified in the model with 89 HFEs with HEPs set to 1.0 and truncation level at 1E-12; while 24,331 combinations were identified in the model with 160 HFEs with HEPs set to 0.1 and truncation level at 1E-11. During this process, combinations of HFEs are programmatically identified and systematic dependency rules are applied. Various importance measures, for example risk achievement (RA), Fussel-Vesely (FV) and dependence importance (DI) are calculated [8, 9]. These importance measures are with respect to the cutset solution obtained by setting the HEPs to 1.0 (or other high values) and are useful to determine the potential impact of dependent HFE combinations should independence not apply between HFEs in a combination.

The analytical part of the HRA dependency analysis [8, 9] is performed in Step 1.4. Combinations can be ranked by the various importance measures. Combinations remain linked to the cutsets in which they are identified, so that they can be inspected by a user to perform a more detailed, contextual dependency analysis than the programmatic analysis.

Table 1: Number of Cutsets for Identification of HFE Combinations for Model with 89 HFEs

Decade	By Decade	Total
1E-1 to 1E-2	2	2
1E-2 to 1E-3	4	6
1E-3 to 1E-4	8	14
1E-4 to 1E-5	55	69
1E-5 to 1E-6	232	301
1E-6 to 1E-7	1889	2190
1E-7 to 1E-8	6819	9009
1E-8 to 1E-9	31230	40239
1E-9 to 1E-10	106523	146762
1E-10 to 1E-11	340813	487575
1E-11 to 1E-12	1097061	1584636

Table 2: Number of Cutsets for Identification of HFE Combinations for a model with 160 HFEs

Decade	By Decade	Total
1E-2 to 1E-3	1	1
1E-3 to 1E-4	10	11
1E-4 to 1E-5	92	103
1E-5 to 1E-6	466	569
1E-6 to 1E-7	2193	2762
1E-7 to 1E-8	12528	15290
1E-8 to 1E-9	57563	72853
1E-9 to 1E-10	246067	318920
1E-10 to 1E-11	998392	1317312

When the analytical part of the HRA dependency analysis is completed, the *HRA Calculator* is used to generate an output file with the HFE combinations and their independent and dependent joint HEPs in Step 1.5. At this point, a user can specify a minimum joint HEP to be applied. In general, the application of a minimum joint HEP is not considered necessary for *PRA Standard* Category II applications, as the application of the systematic dependency rules in the *HRA Calculator* is deemed to be sufficient to demonstrate the levels of dependence applied between dependent events. For *PRA Standard* Category I applications where no detailed dependency analysis is performed, application of a minimum joint HEP is considered necessary. This output file serves as input for the first step in the quantification process described in the next Section.

3.2 Generation of Recovery Rules File

The joint HEPs are applied to the CAFTA cutsets via a post-processing recovery rules file. The generation of the recovery rules file from HRA Calculator output is illustrated in Figure 2 and relies on the *HRACalculator Helper* tool, developed to automate this process.

The output from the *HRA Calculator* is imported into the *HRACalculator Helper* tool in Step 2.1 by user input. The user also specifies the *CAFTA* database ("RR" file) that needs to be updated by addition of the joint HFE basic events that will be applied to the cutsets as recoveries.

In Step 2.2, the recovery rules file in *CAFTA QRecover* rule file format is generated. There are two general approaches to applying the joint HEPs to the cutsets (1) replace the individual HFEs in a cutset with a single joint HFE or (2) apply a recovery factor to the cutset. The advantage of this latter approach is that the individual HFEs are retained in the cutset, which greatly facilitates cutset review and is therefore the recommended approach. There are two options for applying recovery factors; one option ("multiplier") will generate recovery rules that add a dependency factor with a value of 1 or higher, the other option will set the HEPs in an HFE combination to 1.0 and append the joint HFE event to the cutset with its joint HEP as a recovery factor.

A *CAFTA QRecover* recovery rules file that appends a multiplier recovery factor has the following attributes:

1. All HEPs that occur in HFE combinations are retained at their nominal values.
2. The number of allowed recoveries per cutsets is set to 1
3. The HFE combinations are sorted by decreasing combination order. This is necessary to ensure that the highest order combinations are recovered before lower order combinations, which may be subsets of a higher order combination. Should a lower order combination recovery factor first be applied to a higher order combination, given that only one recovery is allowed, the higher order combination would only be partially recovered.
4. The recovery factor to be applied to a combination is a multiplier which is obtained by dividing the joint dependent HEP by the joint independent HEP obtained from the *HRA Calculator* analysis.

A *CAFTA QRecover* recovery rules file that appends a joint HEP recovery factor has the following attributes:

1. All HEPs that occur in HFE combinations are set to 1.0.
2. The number of allowed recoveries per cutsets is set to 1
3. The HFE combinations are sorted by decreasing combination order. This is necessary to ensure that the highest order combinations are recovered before lower order combinations, which may be subsets of a higher order combination. Should a lower order combination recovery factor first be applied to a higher order combination, given that only one recovery is allowed, the higher order combination would only be partially recovered.
4. The recovery factor to be applied to a combination is the joint dependent HEP obtained from the *HRA Calculator* analysis.
5. Adds an independent HEP event recovery factor with the nominal value to cutsets containing only single, independent HEPs that were set to 1.0.

Following generation of the recovery rules, the joint HFE basic events are added to the *CAFTA* database in Step 2.3.

3.3 Seed Optimization

The *QRecover* recovery rules file is imported by the *HRACalculator Helper* Seed Optimizer in Step 2.4 in Figure 2. The seed optimization process was developed to reduce the HEPs - that ideally should remain at 1.0 - to lower values to improve the speed of the cutset solution, which is very desirable if the model is, for example to be used in online risk monitoring. The problem with keeping HEPs at 1.0 is that larger numbers of cutsets needs to be manipulated, which slows processing time down. However, lowering the HEP values may introduce inappropriate truncation concerns.

The philosophy behind this process is to reduce the conditional HEP for a specific HFE to a minimum value that will still ensure that the no conditional joint HEPs in the unrecovered cutsets would be less than the joint HEP that would be applied via the recovery rules file, given that all HEPs may be simultaneously reduced. If the value of the joint HEP in the unrecovered cutsets is the same as the value that would be applied via the recovery rules file, the unrecovered cutset containing the joint HEP would not be inappropriately truncated. For example, for HFEs A, B and C:

Independent HEPs:	$HEP_A = 0.01$, $HEP_B = 0.0001$, $HEP_C = 0.01$
Independent Joint HEP:	$HEP_A \times HEP_B \times HEP_C = 1E\text{-}08$
Conditional HEPs:	$CHEP_A = 0.01$, $CHEP_B = 0.5$, $CHEP_C = 0.06$,
Conditional Joint HEP_{ABC}:	$CHEP_A \times CHEP_B \times CHEP_C = 3E\text{-}04$

In the recovery rules file:

$CHEP_A = 1$, $CHEP_B = 1$, $CHEP_C = 1$
$CHEP_A \times CHEP_B \times CHEP_C \times HEP_{ABC} = 3E\text{-}04$

If HEP_A, HEP_B, and HEP_C are set to $\sqrt[3]{3E-04} = 6.7E-02$, the product $HEP_A \times HEP_B \times HEP_C$ will be 3E-04 before truncation (instead of 1E-08), thus any unrecovered cutset that contains this combination with these values will not be truncated inappropriately. The HEP seed values for this simple example can therefore be reduced from 1.0 to 6.7E-02 without truncation concerns, and processing speed will be improved as fewer cutsets will be generated and carried through the process.

The seed values are generated in Step 2.5 of Figure 2. The seed optimization process needs to consider the impact of lowering an HEP on the joint HEP of all combinations in which the HEP occurs, in conjunction with lowering of all other HEPs. All HEPs are initially set to 1.0. A reduction factor is then recursively applied to the HEPs while all the recovery rules are tested to ensure that the joint HEP for any HFE combination is not reduced to less than the joint HEP specified in the recovery rules file. The *CAFTA* database is populated with the seed values in Step 2.6.

3.4 Quantification Process

The quantification process is illustrated in Figure 3. In Step 3.1, the initial truncation level ("Trunc") is set to the final truncation level achieved in the identification runs ("IDTrunc") from Step 1. The cutsets are generated by solving the single top model using the seed values in the database, recovery rules are applied and cutsets are truncated after applying the recovery rules in Step 3.2. If the cutsets can be generated, they are inspected for convergence by considering the change in CDF in the last decade in Step 3.6. If this is less than 5%, the cutsets obtained in the previous decade are considered converged. If the cutsets are not convergent, the truncation level is lowered and Step 3.2 is repeated.

For models with more than a 100 HFEs or so, the single top model may not solve due to current computer hardware and software limitations. The model then needs to be solved at lower logical levels and the resulting cutsets merged. A first attempt at model solution is made by solving the model on an initiating event basis in Step 3.3. If a specific initiator does not solve, an attempt is made to solve by specific event tree sequence for that initiator in Step 3.4. To reduce the number of recovery rules that need to be processed at sequence level, a sequence-specific identification run can be performed to only identify HFE combinations that are produced by the sequence, and sequence specific seed values and *QRecover* rules file can be generated. However, it is rare that one needs to solve the model at this resolution, and it might be indicative of other modeling issues that ought to be addressed to avoid this. If cutsets are generated at initiator or sequence levels, the resulting cutsets are merged and then inspected for convergence by considering the change in CDF in the last decade in Step 3.6. If this is less than 5%, the cutsets obtained in the previous decade are considered converged. If the cutsets are not convergent, the truncation level is lowered and the process is repeated.

If the cutsets are convergent in Step 3.6, they need to be checked to determine if there are any remaining "unanalyzed" combinations in Steps 3.7 and 3.8. If the truncation level ("Trunc") is equal to or higher than the truncation achieved during the HFE combination identification process ("IDTrunc), *and* if all the seed values are less than or equal to the values used in the identification process, no new HFE combinations should be produced. However, it is often the case that either the truncation level achieved during the identification process is higher than the truncation level where convergence occurs, and/or seed values are higher than the values used in the identification process. In this case, additional HFE combinations could be produced. Such combinations would have their HEPs remain at 1.0 as there would not be any recovery rules applying a joint HFE recovery factor to them. These "unanalyzed" combinations could be important if they skew the results. The efficient way to deal with them is to import (add) these cutsets to the same HRA Calculator dependency analysis database for analysis and generation of additional recovery rules by returning to Step 1.3 for another iteration through the process.

4. CONCLUSION

A systematic process has been developed for integrating HRA Calculator dependency analysis results into a *CAFTA* cutset model necessitated by computer hardware and software limitations. Although *CAFTA* was used in practice, this process could be generalized for application to any other PRA software relying on cutset methodology. The flow charts developed in this paper can serve as a basic framework for developing more detailed user guidance to accompany these software packages.

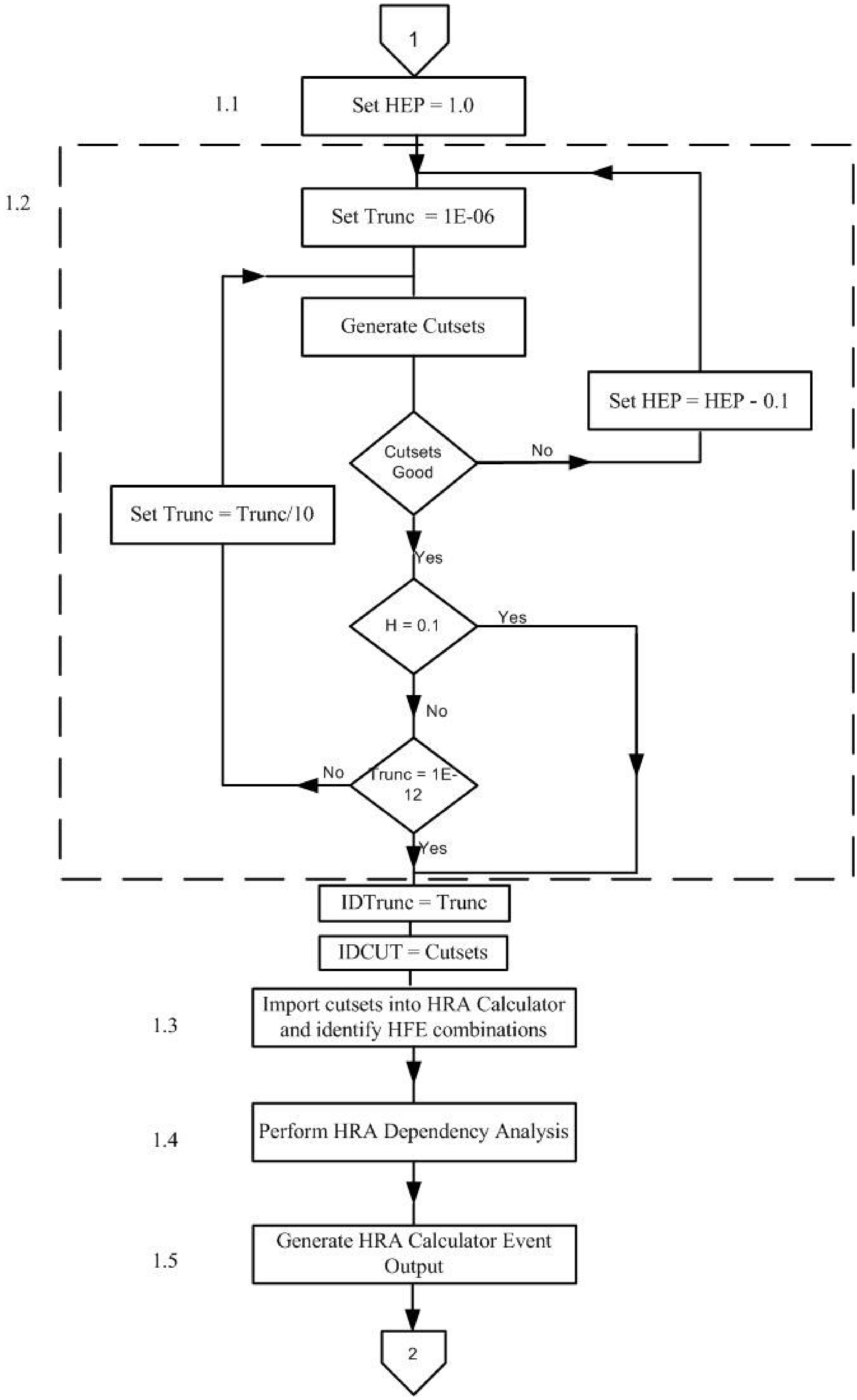

Figure 1: Identification of HFE Combinations and Dependency Analysis

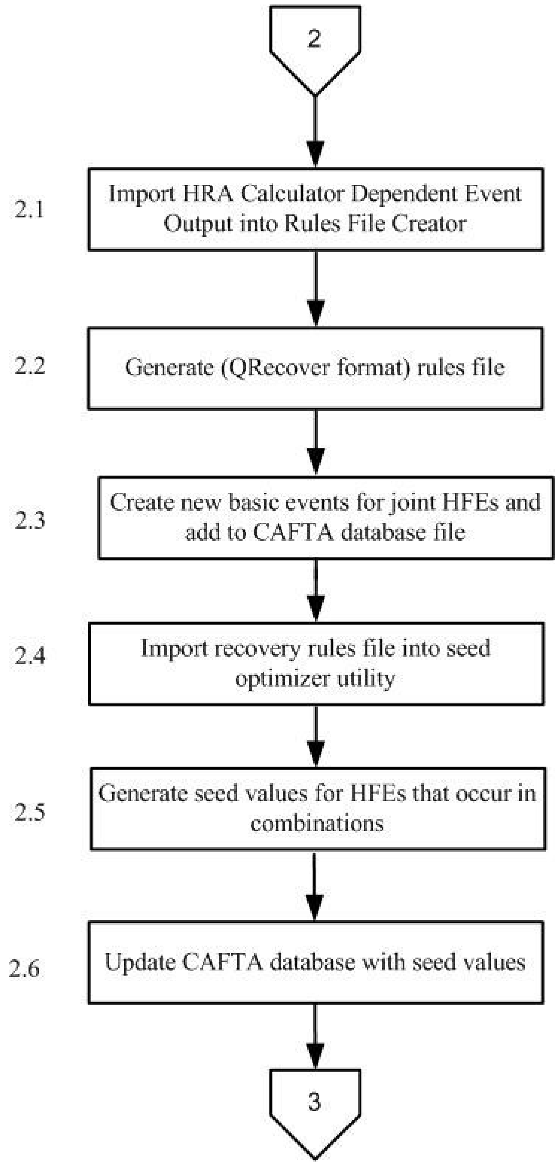

Figure 2: Recovery Rules and HEP Seed Optimization

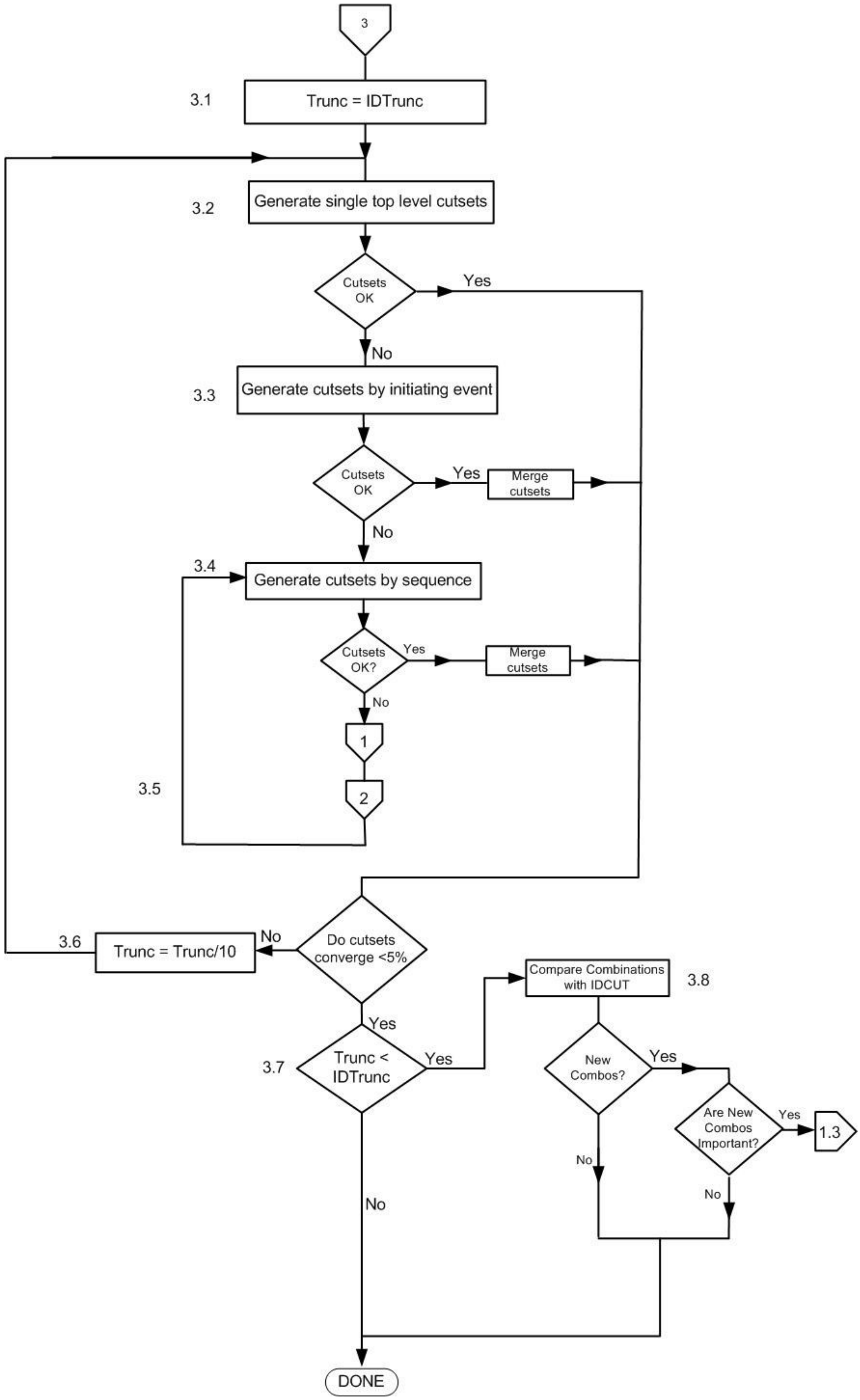

Figure 3: Quantification Process

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