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Original Article

A top-down iteration algorithm for Monte Carlo method for probability estimation of a fault tree with circular logic

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ABSTRACT

Calculating minimal cut sets is a typical quantification method used to evaluate the top event probability for a fault tree. If minimal cut sets cannot be calculated or if the accuracy of the quantification result is in doubt, the Monte Carlo method can provide an alternative for fault tree quantification. The Monte Carlo method for fault tree quantification tends to take a long time because it repeats the calculation for a large number of samples. Herein, proposal is made to improve the quantification algorithm of a fault tree with circular logic. We developed a top-down iteration algorithm that combines the characteristics of the top-down approach and the iteration approach, thereby reducing the computation time of the Monte Carlo method.

1. Introduction

Probabilistic Safety Assessment (PSA) analysis requires the quantification of large fault trees. Fault tree quantification can be done using the minimal cut set method [1], the binary decision diagram method [2], or the Monte Carlo method [3]. The binary decision diagram method provides accurate values but is difficult to apply to large fault trees. The method using the calculation of minimal cut sets is the typical quantification method. This method has several kinds of error in the quantification result [4]. One error is a consequence of using "rare event approximation" or "minimal cut upper bound (MCUB)" method. The second error is a consequence of using "delete term approximation" to handle "NOT gates." The third error comes from the use of truncation value, which can be minimized by establishing an appropriate truncation limit [10].

In addition, in multi-unit PSAs, which have recently been subjected to many studies, it is difficult to calculate minimal cut sets due to the increased size of the PSA models.

The Monte Carlo approach can be used when it is difficult to calculate minimal cut sets or when it is necessary to check the quantification result from the minimal cut set method. The accuracy of the Monte Carlo approach is proportional to the number of samples, and the computation time tends to be proportional to the product of the size of the model and the number of samples. The Monte Carlo method can be applied to very large fault tree; however, the calculation time could be long. For example, it might take several days to quantify all sequences of a large Level 1 PSA model using 10^9 sample size.

This article proposes an algorithm able to reduce the computation time when calculating the top event probability of a fault tree with circular logic. To quantify a fault tree using the Monte Carlo method, it is necessary to determine the state of the top event. A kind of top-down approach can be applied for fault trees with circular logic (called the top-down circular approach in this article) [5]. However, the top-down circular approach generally takes a long time. Therefore, an iteration approach is actually used.

We have reviewed the characteristics of existing approaches and developed a new approach, called the top-down iteration approach in this article, which combines the advantages of the top-down and iteration approaches.

We have developed and used software called FTeMC [9], which performs quantification of fault trees using the Monte Carlo method. All approaches discussed in this article have been implemented in FTeMC so that a user can select a calculation option.

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Section 2 describes the features of existing approaches and the new top-down iteration approach. Section 3 compares the calculation time of each approach for several fault tree models, and Section 4 provides a summary and conclusions.

2. Monte Carlo method for fault trees

2.1. Basic algorithm for the Monte Carlo method

The Monte Carlo method is to estimate the occurrence probability by testing how many times it occurs out of a number of trials. The basic algorithm of the method for calculating the top event probability of a fault tree is illustrated in Fig. 1.

- Repeat the following steps for N number of samples.
  - Determine the state (failure or success) of each basic event randomly.
  - Determine the state (failure or success) of the top event, and increase the failure count F if the state of the top event is true.
- If F failures occur during N trials, the top event probability is evaluated as F/N.

Let me show an example. It consists of three gates and three basic events as shown in Fig. 2. For each trial, the states of basic events are determined randomly. For example, A and C are True, and B is False at the first trial. Then, G1 and G2 are True, and in turn, TOP is True. For the second trial, A is True, and B and C are False. Then, G1 is True, and G2 is False, and in turn, TOP is False. The procedure is repeated for the sample size. If TOP is True two times out of three trials, the top event probability is estimated as 2/3.

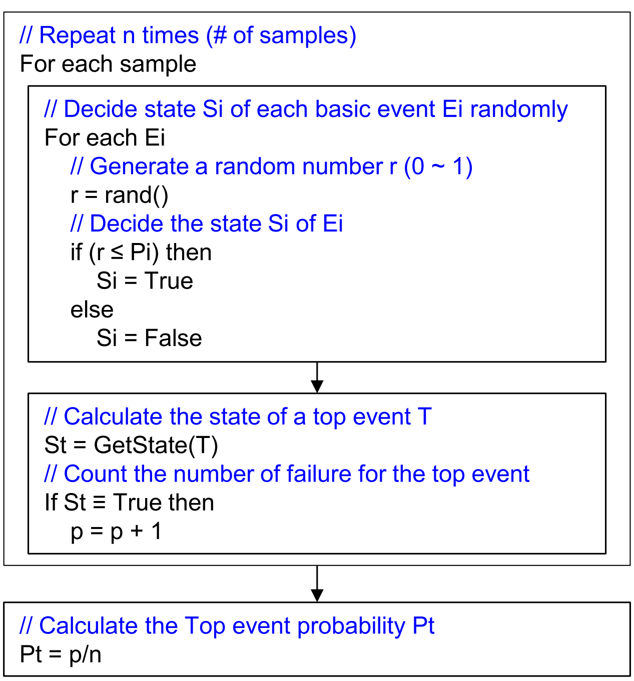

Fig. 1. Monte Carlo main algorithm.

For large fault trees, it takes much time to determine the state of the top event. One of the following approaches can be used to determine the state of the top event:

- The top-down approach is used for a fault tree without circular logic.
- The top-down circular approach can be used for a fault tree with circular logics, but it takes a lot of calculation time.
- The iteration approach has been used for a fault tree with circular logics.
- A new top-down iteration approach is developed for a fault tree with circular logics.

The first three approaches, the top-down, the top-down circular, and the iteration approaches have been used previously and are described in Section 2.2–2.4, respectively. Section 2.5 describes the top-down iteration approach developed in this article.

2.2. Top-down approach

For a fault tree without circular logic, the top-down approach is effective in determining the state of the top event. Figs. 3 and 4 show the algorithm of the top-down approach. This algorithm starts from the top event and determines the state of the top event using the states of the children. The state of each child is determined using the states of its children, in turn.

GetState is a function that gets the state of each gate or basic event. To save computation time, a vector C is introduced to indicate whether the state of each gate has already been computed. This saves the calculation time by not recalculating the state of an already calculated gate.

The state of the undetermined gate is calculated using the states of its children. This process is described in a subfunction CalculateGateState. Each child's state is computed using the GetState function recursively.

Inside CalculateGateState, if the gate state is determined during calculation, we do not need to check the remaining children. For example, in the case of OR gate, if any of the children is true, the state of the gate is true; so, the rest are skipped without calculation. This process is important for reducing calculation time.

2.3. Top-down circular approach

In the presence of circular logic in a fault tree, the top-down approach cannot be used because an infinite loop is encountered.

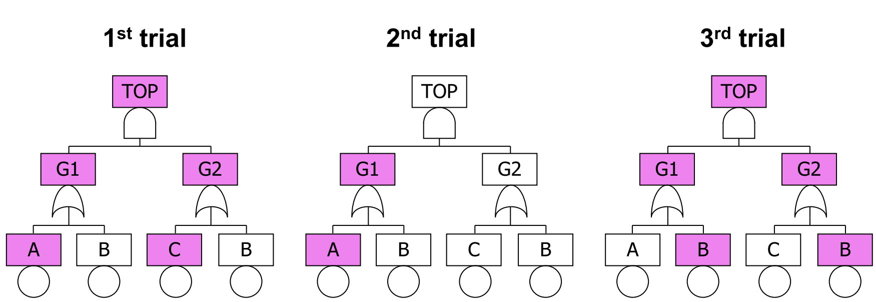

Fig. 2. An example of Monte Carlo method.