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A comparison of dynamic event tree methods – Case study on a chemical batch reactor

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A B S T R A C T

Dynamic event tree (DET) analysis, one of the main dynamic Probabilistic Safety Assessment methods, provides a framework to capture the effect of dynamics on the risk estimate. Depending on how continuous stochastic variables (CSVs) are treated, DETs can be classified into discretization- or sampling-based methods. The accuracy of the estimate and required computational resources depend on the method chosen as well as the nature of the problem. CSVs also include variable initial conditions, some of which significantly impact accident evolution. This work compares alternative DET methods in terms of numerical accuracy and computational resources for a case study of a chemical batch reactor problem, a system sensitive to both accident dynamics as well as variable initial conditions. The reference solution is a computationally intensive analog Monte Carlo simulation. The results show that the DET methods fairly match reference results with significantly less computation required. Further, in light of epistemic uncertainties of model parameters, this paper presents a comparison of DETs that includes detailed analyses of contributors of risk and its uncertainty, which unfolds the strengths and weaknesses of discretization and sampling based DETs.

1. Introduction

The variability in accident initial conditions (e.g. size or location of breaks for a loss of coolant accident in a nuclear power plant, process parameters such as coolant inventory at the accident initiation, decay power, etc.) can drive accident evolution in addition to the time dependent interactions among physical process, safety equipment and operator actions, affecting sequence outcomes and ultimately risk estimates. Epistemic uncertainties in the parameters of these models (e.g. physical model parameters such as heat transfer coefficient, discharge coefficient, etc. and parameters of stochastic models of safety system responses such as demand failure probability of equipment, human error probability, etc.) might also influence risk estimate, its key contributors, and their uncertainties [1]. Probabilistic Safety Assessment (PSA) as applied in Nuclear Power Plants (NPPs) accounts for accident dynamics with plant simulations during success criteria analysis and also propagates stochastic PSA model parameter uncertainties with Monte Carlo simulation approach. In current PSA practice (Level-1), the effects of accident dynamics, variability in initial conditions, and uncertainties in physical model parameters (e.g. Thermal-Hydraulic models in NPPs) are conservatively bounded in accident sequence modeling.

To capture the effect of dynamics in risk and reliability assessments, many methods were developed and applied to different complex systems. These dynamic PSA methods include analog Monte Carlo simulation [2], continuous event tree [3], dynamic event tree [4], dynamic flow graph methodology [5], Markov modeling/Petri-nets, dynamic fault trees, etc. Of these, the Dynamic Event Tree (DET) provides a framework to capture the impact of accident dynamics on the risk estimate directly. The coupling of plant physical models with a stochastic model of the safety system response (failures to start and run of safety equipment) and their integrated simulation, the essential feature of DET, can also model the impact of the variability of initial conditions as well as allows uncertainties in both models to be propagated to risk estimates. Although the DET provides a potential solution to treat dynamics considering variability in initial conditions and propagate both uncertainties (physical and PSA), there are practical challenges in implementation of DET approaches, especially optimal balance between numerical accuracy and number of computations. To improve the practicality of DETs, it is necessary to assess the strengths and weaknesses of the current DETs, which can be realized by a comparison of the DETs with a reference solution.

Implementations of DETs reported in the literature include ADS [6], MCDET [7], SCAIS [8], ADAPT [9], RAVEN [10], etc. These DETs share the same basic approach of integrated accident simulation to investigate accident dynamics, as developed at the initial stages [4]; in a DET simulation, after each discrete time step of accident simulation, the response

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of process variables, safety equipment and operator actions are checked for possible branching and potential sequences. Plant simulators are normally coupled with the DET tools. There are also a few differences among DET tools arisen while addressing complexities in DET quantification of risk, e.g. continuous variables, support system dependencies, etc. Depending on how continuous aleatory variables are treated in DET simulations, the above mentioned DET methodologies/tools can be classified into two distinct methods, namely the Discrete DET (DDET, e.g. ADS) and the Sampling DET (e.g. MCDET) approaches. The primary difference is that continuous aleatory variables (e.g. recovery time, operator response time, failure time of equipment, etc.) are discretized in DDET while the same variables are sampled with Monte Carlo simulation in the latter (with each sample represented by a DDET). Such a difference in approach could impact the accuracy of final results as a function of number of computations when many continuous variables are present in the accident sequences. This work compares these DET approaches in terms of numerical accuracy and computational resources and suggests the required improvements to match more realistic reference results. The reference method is computationally intensive dynamic PSA with Analog Monte Carlo. The method Analog Monte Carlo simulation estimates the risk measures from a randomly chosen sample of sequences.

This paper compares the DET methods in the analysis of a chemical batch reactor problem. The chemical batch reactor problem [11] is chosen because of its relatively simple numerical solution compared to complex NPP simulations, which allows alternative approaches to be examined and evaluated quickly. Analog Monte Carlo results reported in ref. Podofillini and Dang [11] are used as a reference result in the current study. The continuous variables driving the accident scenario include a few initial conditions (e.g. reagent concentrations in the batch reactor inputs, coolant mass flow, etc.) and the timing of two operator actions required in response to unexpected or upset conditions. The current study adopts the physical, safety equipment, and operator models as well parameter data from ref. [11]. Considering accident dynamics and variability in initial conditions, each of the DET methods is applied and the obtained risk estimates are compared to the reference result.

In estimating risk, accounting for accident dynamics enhances the realism, while propagating uncertainties adds credibility to the results. As applied in PSA of NPPs, DET methods also use an outer loop around DET simulation for propagating epistemic uncertainties. In this work, in light of epistemic uncertainties, the differences between DETs (sampling vs discretization of continuous variables) is tested thoroughly, in particular detailed insights such as important contributors to risk and uncertainty. A comparison is performed between DETs considering epistemic uncertainties of models on the batch reactor, which further exposes the strengths and weaknesses of each method.

The paper is organized as follows: Approach for comparison and the methods under consideration are briefly discussed in Section 2. Section 3 presents the DET models and computational framework for the batch reactor problem. The obtained DET results and their comparison with the reference results are discussed in Section 4. Section 5 presents a comparison of DETs in light of epistemic uncertainties. Finally, the conclusions are given in Section 6.

2. Approach for comparison and methods under consideration

2.1. Approach for comparison

A comparison of the DET methods with a reference solution helps to identify their specific weaknesses, which will be explored further to identify measures to improve the methods. To ensure a thorough and realistic comparison, the analysis considers accident dynamics, variability in initial conditions, as well as epistemic uncertainties in obtaining the results. As a basis for comparison, both accuracy in the obtained results as well as total computations involved are used. The results include not only the overall risk estimate, but also specific risk contributors such as important sequences and events and uncertainty contributors.

A comparison of methods requires defining a set of comparison metrics, the common conditions required to perform their calculations, and a reference solution. Comparison metrics include measures such as: risk estimate viz. failure frequency, risk contributors viz. Fussell-Veseley importance measure, and critical accident sequences viz. top minimal cut sets. Comparison with epistemic uncertainties additionally includes ranking of epistemic parameters based on uncertainty importance measures viz. Pearson correlation coefficient. Common conditions to perform calculations are defined viz. the allocated computational resources. A reference solution is obtained for comparison purposes through an Analog Monte Carlo simulation. Calculations are initially performed for various methods (DET) under consideration without uncertainties and compared with the reference solution to assess their respective strengths and weaknesses. Measures are investigated to improve the DET methods and subsequently their effectiveness is evaluated further in a comparison considering epistemic uncertainties. As comparison with epistemic uncertainties demand intensive computations, only a few select methods from the initial list of DET methods are chosen for further analysis.

2.2. Methods under consideration

DET analysis was used in several safety studies to investigate the accident dynamics of various accident scenarios [7,12–13]. Compared to classical PSA event tree/fault tree, DETs can limit the detrimental effects of grouping of the sequences and of bounding criteria, thereby helping to avoid defining non-optimal success criteria, which may distort risk [14]. As mentioned earlier, DETs can be classified into two types based on how they treat continuous stochastic variables, namely DDET and MCDET. When the response of a safety system is continuous, e.g. operator action times (OAs), the DDET approach discretizes the response while MCDET approach samples randomly from the distribution for the stochastic variable. In MCDET, branching does not take place when there is a demand for a system that has continuous response, but rather simulation continues with a single sampled response. However, a sufficient number of random samples are needed in sampling-based approaches (e.g. MCDET) to estimate the risk. For example, ref. Janssen [15] discusses some of the methods for convergence in sampling approaches. In DDET, the continuous probability distribution is discretized into a finite number of intervals where representative values for the intervals are used in simulations [13]. Discretization of continuous probability distributions has also been used in other applications [16].

Initial Conditions (ICs) at the time of accident initiation can influence the accident evolution and the resulting sequences. The structure of DETs can easily account for the variability in initial conditions while simulating the accident scenarios. The consideration of initial conditions introduces complexity in DETs as many are continuous variables. The need to model continuous stochastic variables including initial conditions in dynamic simulations yields four classes of DET methods, where discretization or sampling is the essential difference. Besides continuous stochastic dynamic variables such as operator response time, recovery time, etc. in DET simulations, initial conditions are also subjected to sampling or discretizing. This results in the four DET methods as shown in Fig. 1. The first DET method samples both dynamic variables and ICs while the fourth method discretizes both dynamic variables and ICs. The second method samples ICs and discretizes dynamic variables while the third DET method does the opposite.

The reference solution, an analog Monte Carlo simulation, is a stochastic simulation of system behavior, where stochastic variables are sampled to determine initial conditions, availability of equipment, operator response/execution times, etc. The end state of the system is obtained in each simulation along with a record of component responses. Numerous stochastic simulations are repeated and the risk and reliabil-