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Some acceleration methods for Monte Carlo simulation of rare events

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Abstract

The reliability analysis of instrumented safety systems is an important industrial issue. The standard modeling languages (e.g., Fault trees, Markov chains) and methods employed for these studies become difficult to apply mainly because of the increasing complexity of the operating context (e.g., maintenance policies, ageing process). Thus, a powerful alternative is Petri nets associated with Monte Carlo simulation (MC). However, obtaining accurate estimators on rare events (system failures) requires very long computing times. To address this issue, common methods are not well-suited to Petri Nets whereas the "Méthode de Conditionnement Temporel" (MCT), a truncation method, seems to be. Indeed, MCT is independent of the duration distributions involved in a model. However, it is only defined when the rare event consists in reaching an absorbing state. To overcome this limitation, we first propose an extension of MCT (EMCT) to cases of repeated cycles where the failure event is either direct or in competition with other events. Numerical results show that EMCT gives better estimates than MC. Second, we introduce a new computational technique, called Dissociation Method, for systems with independent components. We combine it with both MC and EMCT. Through different numerical examples, we observe a significant improvement of the results.

Keywords: Reliability analysis, Petri Nets, Fast Monte Carlo simulation method, Dissociation method, MCT.

1. Introduction

The reliability analysis of instrumented safety systems is an important industrial concern in many fields such as public transportation, power plant and oil and gas installations. The study of such equipment becomes more and more complicated mainly because of the progress of the operating context (maintenance policies, ageing process, climate changes, subsea installations, ...). Consequently, to take into account the mathematical model corresponding to these real-world systems, the standard modeling languages may be less and less appropriate. Indeed, Fault Tree [1] is an approach which only models independent components, thus, this method is not relevant to treat components submitted to the same repair team for instance. Moreover, multi-phase Markov processes [2] are limited to exponentially distributed transitions between states (it can be bypassed but it leads to models with potentially huge state space and can be too complex in practice), hence, this approach is not well-suited to model the ageing process of the components with a Weibull distribution. Therefore, Petri nets [3] offer a powerful alternative [4]. Furthermore, traditional analytic or numerical methods employed for analysing the performance of these reliable systems are difficult to apply, or even no more valid. This is due to the size and the stringent hypotheses of the model, and also, to the intricacy of the formulation and computation of the required dependability indicators. Thus, Monte Carlo simulation becomes a relevant option to be able to obtain approximated numerical results.

Given these considerations, one solution to carry out reliability analysis on instrumented safety systems is to combine the Monte Carlo simulation with Petri Nets. However, these instrumented safety systems have to be very reliable specially when they represent the ultimate safety barriers to prevent disastrous events. In Oil and Gas industry, those systems are called High Integrity Protection Systems (HIPS) [5]. For instance, the HIPS is able to detect an overpressure in the installation thanks to sensors, and to eliminate the source of the problem by closing appropriate valves, which avoids the explosion of downstream equipment. Thus, the failure of such a system is by definition a rare event, that must be limited. To do this, their components are tested during periodic interventions in order to detect hidden failures, and then the revealed failures are fixed by repair teams. Then, a problem with the Monte Carlo simulation remains when we want to obtain accurate estimators on such highly reliable processes. Indeed, the simulation of a rare event (system failure) requires a very long computing time.

To address this issue, some fast simulation techniques have been developed. We can classify these Variance Reduction Methods (VRM) in two main families: Importance Sampling (IS) [6, 7, 8] and Multilevel Splitting [9]. The main idea of IS is to change some probability distributions of the model associated with the event of interest by taking into account the other model distributions in order to increase the occurrence of the rare event (e.g., to transform the parameters of the failure distri-

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