Some Notes on Rare-Event Simulation Challenges

Fast Abstract

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ABSTRACT

Rare-event simulation methods have led to promising algorithms for the quantitative evaluation of systems which are both too complex for a numerical analysis and suffer from unacceptable simulation run times. Dependability prediction during the design of real-life size industrial systems, for instance, can benefit significantly from progress in this field. However, there are still some gaps to be filled to allow general applicability of the existing methods. This fast abstract points out open issues to promote discussion of future research directions in this field.

CCS CONCEPTS

• **Computing methodologies → Rare-event simulation**; **Discrete-event simulation**; *Simulation tools*;

KEYWORDS

Rare-event simulation, challenges, discrete-event systems

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1 INTRODUCTION

Rare-event simulation is an umbrella term for several methods that speed up simulations of (discrete-event) models, in which states of interest are visited only rarely, thus leading to unacceptable run times. Such algorithms are useful when state-level numerical methods are infeasible because numerical restrictions (i.e., non-Markovian delays), a large state space, or because the underlying stochastic process of the model does not allow a direct solution [2]. Among the known algorithms, two classes in the literature are multilevel splitting [5] / RESTART [9] and importance sampling [6]. However, they are not easily applicable to real-life applications by non-experts, as they typically allow quite restricted models only or require deep mathematical insight into the model behavior.

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This paper gives a (probably rather) subjective and incomplete view on open issues still obstructing general use of rare-event simulation methods in practical applications, and highlights possible research directions. The text is structured along topics connected to models and performance measures, algorithms, software tool implementations, and foreseeable applications. Size restrictions do not allow a comprehensive literature analysis here.

2 CONSTRUCTION OF ACCURATE MODELS

The construction of application-specific mathematical models for a certain problem, as often done in mathematics, may have the advantage of the ideal mix between level of detail and analyzability. However, this is only possible for specialists in the underlying models and not for system designers. An intermediate description level is needed, that both 1) fits the type of applications while 2) still allowing a performability analysis. Markovian models are too restricted for many realistic engineering applications, though. Low-level simulation languages can be used similarly to programming languages to specify very detailed system behavior, but as the code itself is the description, there is no good way of reusing information from the model to speed up a rare-event simulation.

We believe that a better description trade-off is possible with standardized formal models having a clear semantics such as Petri nets or queuing networks. For an even better user-side accessibility, domain-specific languages and models are being investigated and developed in last years, being suitable for evaluation of properties of interest when a property-keeping transformation into a well-understood model is possible. To make matters worse, one single model class may not be sufficient to describe all parts of a system properly, since there may exist subsystems with either discrete or continuous characteristics, or traditional models from different engineering disciplines. Mixing, interfacing or translating such models for a complete description and joint simulation is a challenge in itself [4], but must be further extended to make rare-event simulation applicable to them.

3 PERFORMABILITY MEASUREMENTS

Performance measures are model-level specifications of system design questions, and the usual assumption of a simple hitting probability of a dangerous state must be extended significantly. Extensions in other areas include impulse and rate rewards assigned to events and states, and aspects of state-event trajectories used in the expressions of stochastic model checking. Evaluation approaches must cover both steady-state and transient observations.

For a more general applicability of rare-event simulation results, the usual assumption of just one state (set) of interest must be overcome. There is no clear qualitative distinction between rare-event and "normal" simulations, but a smooth transition instead. In the end, a user is interested only in the evaluation of a (possibly) complex measure expression, which may contain terms exhibiting rare-event characteristics. Hence, it is not simply a question of the rarity in which the simulation visits a state (set), but its corresponding measure weight — a rarely hit state is fine as long as the reward collected in it is small. In fact, it is not important whether a state is rare, only if its corresponding measure makes it important. This requires an adapted concept of rarity and corresponding simulation algorithms.

4 AUTOMATIC ALGORITHMS

Fully automatic algorithms are necessary to detect rare-event problems or unify their treatment with that of regular simulation problems [10]. The regions of interest have to be derived from the system models and complex performance measures in the mentioned sense. Multiple regions with rare events have to be covered correctly and efficiently. An even more general view is necessary: a system model should be abstractly viewed as describing a state space with attractor and deflector regions, i.e., where a simulation will be pulled towards or pushed away, taking into account the weight that the performance measure assigns.

New methods should be developed, that are able to derive these regions on a higher level of abstraction and to check if they were visited by a simulation enough, or to compute configuration elements such as an importance function for a splitting simulation. For the described set of extended problems, the notion of simulation efficiency has to be broadened for instance by requiring that similar amounts of simulation effort are spent on all paths towards state regions of interest. It cannot be expected from a systems designer to specify an importance function and thresholds of a splitting simulation, for instance. Automatic derivation of existing methods [1, 11] are still quite restricted and have to be extended. In this regard, recent advancements in throughput bound computation [7, 8] may serve as an improved baseline to automatically incorporate "path rareness" directly into the importance function.

Research activities may use information derived from the model structure in a better way, reuse previous simulation results incrementally, or transfer and adapt methods from other areas such as graph-based searching, (robotic) path planning, or even AI-inspired techniques to find state trajectories towards rare regions of interest.

5 AVAILABILITY OF SOFTWARE TOOLS

So far, only a few software tools are available that implement rare-event simulation, which are still restricted to academic prototypes. For a better visibility and application, those tools must be enhanced, and newly developed methods must be integrated into existing industry-grade tools. An important step for this integration may be a modular implementation of rare-event algorithms that are independent of the applicable models, by defining an API-like software interface and a description of basic requirements for a model class to make it accessible for rare-event simulation. This will allow developers to integrate new algorithms into several tools in a fast and easy manner. Similarly, visibility of rare-event research results can be significantly increased by a modular software framework allowing integration and comparison of new algorithms as well as by creating a dataset of benchmark models with known results and achieved speeds to compare new ideas.

6 POTENTIAL APPLICATIONS

Research activities and motivation in rare-event simulation would profit from visible successes in industrial applications. However, this will require to detect potential contributions and solve real-life problems. We believe that there is ample opportunity in many relevant engineering fields which still nowadays use old and restricted methods often out of tradition or unknown better options (e.g., fault trees for nuclear plants). However, with the increasing importance of complex engineering systems in daily life, non-functional system aspects as well as formal evaluation as part of certification procedures become more important. While this is becoming more accepted today, there is still a need for corresponding methods [3].

Important areas of systems design with trade-offs between dependability and other properties include avionics, automotive, transport, supply chains, IoT, real-time systems, distributed systems, communication networks, etc. A comprehensive buzzword area containing some of these are *resilient cyber-physical systems*.

7 CONCLUSIONS

The rare-event simulation community developed several powerful methods that allow the evaluation of the dependability of dynamic systems. This short paper gives a brief overview of some open issues and research directions in this area, which shall be tackled towards more general applicability and successful industrial use.

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