Dynamic Risk Assessment Framework with Limit Surface Search and Success and Failure Domains Analysis

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EXTENDED ABSTRACT

Risk assessment is crucial for ensuring operational safety and managing risk of nuclear power plants (NPPs). Probabilistic safety assessment (PSA) combined with deterministic analysis using physical plant models serves as the primary methodology for this purpose. Since accident scenarios are potentially unlimited, PSA adopts a practical approach of selecting representative scenarios with conservative assumptions. These scenarios are organized as event trees (ETs), while component-level basic events that cascade to cause system-level failures on ETs are structured using fault trees (FTs).

PSA has been widely applied in various contexts; however, potential gaps may exist in scenario coverage. To address this limitation, dynamic risk assessment has been investigated over recent decades. In this assessment, factors affecting accident progress are considered in much greater detail. Theoretically, possible accident scenarios considering such factors are unlimited. Therefore, a central challenge in dynamic risk assessment methodology is how to investigate potential accident scenarios effectively. For instance, PSA and deterministic analysis can operate in a synchronized manner, in which dynamic ETs are developed by branching event sequences when plant status meets user-defined rules [1]. Various other dynamic safety assessment methods have also been suggested. However, practical challenges of these methods include the exponential growth of scenario numbers, and the substantial computational resources required to analyze them.

In this paper, we present a dynamic risk assessment framework with limit surface search and success and failure domains analysis. The key feature of the presented framework is that possible dynamic scenarios are predefined and pruned after simulations, unlike conventional dynamic approaches that develop scenarios in parallel with deterministic analysis. This post-pruning approach enables the adaptation of simulation optimization algorithms to predefined scenarios for addressing computational resource problems.

Figure 1 shows the overall schematic of the proposed framework, which consists of three parts. First is the deep-learning based searching algorithm for informative limit surface/scenarios/states (Deep-SAILS) [2]. This algorithm identifies the limit surface by iteratively updating a deep learning (DL) metamodel that predicts critical parameters representing scenario consequences, such as peak cladding temperatures (PCT). The iterations include simulation of scenarios estimated to be close to the surface by the DL metamodel and subsequent training of the metamodel. Through these iterations, the limit surface can be pinpointed, and simulation can be optimized for scenarios close to the surface, as shown in the right panel of Fig. 1(a).

Second is optimized and accelerated simulation using intermediate storage (OASIS) [3]. Even when optimized with Deep-SAILS, the computational time required for simulations is typically substantial. OASIS further saves this time by avoiding redundant simulations of scenario timelines with identical plant conditions, as shown in Fig. 1(b). For this purpose, restart points of simulated scenarios are identified and cached in storage, then compared with given scenarios to provide the optimal starting point for simulation. Additionally, deterministic analysis becomes more efficient through parallel execution of multiple simulations.

Third is automatic accident sequence generation [4]. The combination of Deep-SAILS and OASIS can locate the limit surface with minimized computational effort; however, interpretation and practical usage of the surface can be complex when more dynamic factors are considered due to high dimensionality. To address this challenge, the generation algorithm analyzes success domains and locates multiple boxes containing only success scenarios. The locations of these boxes are optimally determined using an alpha-shape method, and the regions segmented by the located boxes are converted into dynamic ETs or other comprehensible forms, as shown in Fig. 1(c).

We believe this novel framework can serve as a complement to both existing dynamic risk assessment methods and conventional PSA. Further study will be conducted to assign quantified risk measures by either utilizing existing reliability data or employing a novel risk index.

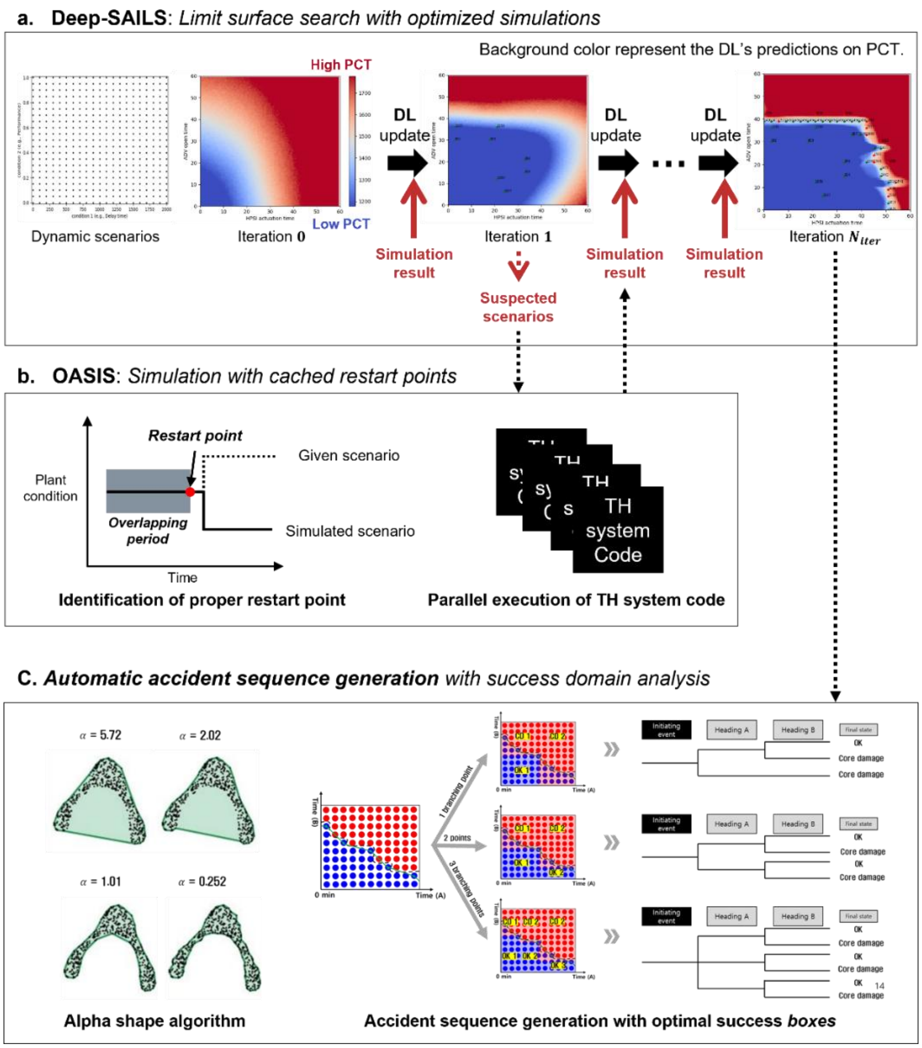

FIGURE 1. Overall schematic of the proposed dynamic risk assessment framework

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