

Reassessing Nuclear Risk Assessment Using Marked Point Processes and Discrete-Event Simulation: Challenges and Opportunities

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Abstract

Classical Probabilistic Risk Assessment (PRA), as developed through the Reactor Safety Study and subsequent industry practice, has provided a foundational framework for nuclear risk quantification. However, its reliance on steady-state availability metrics, infinite time horizons, memoryless initiating event processes, and static fault-tree logic is increasingly difficult to reconcile with modern operational and regulatory realities.

This paper examines the reformulation of nuclear risk assessment as a time-domain stochastic process problem using Marked Point Process (MPP) and Discrete Event Simulation (DES). In this framework, system behavior evolves as a stochastic state process driven by failures, external hazards, maintenance, testing, and operational decisions. Accident occurrence is represented as a counting process derived from these state trajectories, enabling direct evaluation of Expected Time To Accident (ETTA) distributions, exposure durations, and configuration-specific risk under time-varying and dependent conditions—quantities not readily available from classical cut-set methods.

The framework relaxes key PRA assumptions by introducing finite-horizon evaluation, state-dependent initiating events, and explicit modeling of repairable systems with imperfect maintenance. Maintenance efficacy is represented stochastically, capturing degraded and “better-than-new” outcomes and their effect on future failure exposure. The framework also reframes common-cause failure as a dynamic phenomenon subject to detection and correction over time, rather than a persistent latent characteristic.

These capabilities support direct evaluation of tradeoffs between prevention and mitigation. Historical experience from the Emergency Core Cooling System (ECCS) hearings [1] underscored uncertainty in protection-system performance and the importance of containment as a final barrier. Within the MPP/DES formulation, both accident occurrence and post-accident consequence exposure can be quantified over finite horizons, supporting a regulatory strategy that relies on established standards for core-damage prevention while evaluating containment under the assumption that core damage has occurred.

The transition to MPP/DES carries practical challenges: increased computational demand for rare-event simulation, expanded data requirements, and questions of model interpretability. At the same time, the approach aligns naturally with risk-informed, performance-based regulation—including frameworks envisioned under 10 CFR Part 53—and with the transparency requirements reinforced by recent judicial developments such as *Loper Bright Enterprises v. Raimondo*. Future work should address efficient simulation methods, parameter estimation from operational data, and regulatory metrics suited to time-domain risk representations.

1 Introduction

Probabilistic Risk Assessment (PRA), as formalized in the Reactor Safety Study and refined through decades of industry practice, has served as the primary analytical framework for quantifying nuclear

power plant risk. Its widespread adoption has supported risk-informed decision-making across design, operation, and regulation. However, the mathematical structure underlying classical PRA relies on assumptions that are increasingly difficult to reconcile with the operational and regulatory context of advanced reactor systems. These include steady-state availability metrics, effectively infinite time horizons, independence and memoryless initiating event processes, and the representation of system behavior through static fault-tree logic.

At the same time, emerging regulatory frameworks, including risk-informed and performance-based approaches such as those envisioned under 10 CFR Part 53, place greater emphasis on demonstrable system performance over time, explicit treatment of uncertainty, and transparent linkage between design choices and safety outcomes. These expectations challenge the traditional PRA paradigm, which expresses risk primarily as long-run frequency metrics derived from combinatorial approximations.

In response to these limitations, recent work has explored the formulation of nuclear system risk as a time-domain stochastic process problem using Marked Point Process (MPP) and Discrete Event Simulation (DES). In this approach, system behavior is modeled as a stochastic state process evolving through failures, external hazards, maintenance actions, testing, and operational decisions. Accident occurrence is represented as a counting process derived from these state trajectories, allowing direct evaluation of Expected Time To Accident (ETTA) distributions, exposure durations, and configuration-dependent risk.

While dynamic simulation approaches to reactor safety analysis have been developed, including dynamic probabilistic risk assessment and discrete-event simulation methods [2, 3], these approaches typically continue to represent system behavior through event-tree logic and scenario-based simulation rather than through an underlying stochastic process formulation.

Earlier work explored the use of marked point processes in nuclear safety analysis [4], demonstrating the potential to represent hazard evolution and operational decision-making within a stochastic framework. That work, however, was directed primarily toward living PRA, risk follow-up, and operational optimization, including surveillance testing and shutdown criteria, rather than toward finite-horizon protection system quantification and accident progression for licensing analysis. In particular, while Holmberg incorporated process lifetime within an optimal control framework, the formulation did not explicitly address accident progression, normal process termination, nor the role of maintenance-driven removal of failure modes in shaping future system vulnerability.

As a result, failure and recovery mechanisms in most existing approaches are modeled as conditional events within predefined logical structures rather than as time-evolving processes governed by state-dependent dynamics. By contrast, the MPP/DES framework adopted here treats failure occurrence, maintenance, and corrective action as components of a stochastic process, enabling direct representation of how system vulnerability changes over time. This distinction is particularly important for capturing maintenance efficacy, root cause analysis, and failure mode removal, all of which influence future system exposure but are not naturally represented within traditional or simulation-augmented PRA formulations. These relationships have been examined previously in [5], where limitations of combinatorial logic-based approaches were identified in the context of protective system management. The present work extends that perspective by embedding these concepts within a stochastic process framework, enabling explicit representation of time-dependent system evolution and finite-horizon risk evaluation relevant to licensing analysis.

While this formulation offers a more physically and operationally faithful representation of system behavior, it introduces nontrivial challenges. High-fidelity DES models can require substantial computational resources, particularly when evaluating rare-event behavior. The approach also demands richer data, including time-dependent failure characteristics, repair duration distributions, and quantitative representations of maintenance effectiveness and dependency structures. In addition, the increased model fidelity raises questions regarding appropriate levels of abstraction, interpretability, and consistency with regulatory decision processes.

Despite these challenges, the MPP/DES framework provides capabilities that are difficult to achieve within classical PRA. By representing system evolution directly in time, the approach enables analysis of maintenance scheduling, configuration-specific vulnerabilities, common-cause influences, and environmental stressors within a unified structure. It also supports evaluation of tradeoffs between prevention and mitigation strategies, including the role of containment as a primary barrier to public risk in the presence of residual uncertainty in protection system performance.

Historical experience, including the Emergency Core Cooling System (ECCS) hearings [1], highlighted substantial uncertainty in protection system performance under accident conditions and reinforced the role of containment as a final barrier to public risk. Within a time-domain stochastic framework, such tradeoffs can be evaluated directly by quantifying both accident occurrence and post-accident consequence exposure over time.

Recent work by the authors has developed several aspects of the stochastic process-based approach described here, including applications to generation risk assessment, protection system modeling, reinterpretation of Common Cause Failure (CCF) mechanisms, and broader system planning and cost-risk structures [6, 7, 8, 9, 10]. Related extensions are also being pursued through ongoing collaborative efforts, including a recent DOE Nuclear Energy University Program proposal (RPA-26-38792), although those efforts do not explicitly address the practical challenges associated with transitioning from classical PRA to an MPP/DES framework.

The contribution of this paper is not to review dynamic safety analysis generically, but to clarify what is required to transition from classical PRA to an MPP/DES formulation in a licensing-relevant setting. In particular, the paper identifies the practical challenges associated with finite-horizon accident quantification, explicit modeling of maintenance efficacy and corrective action, dynamic representation of dependencies and failure mode removal, and interpretation of the resulting time-dependent metrics for risk-informed, performance-based oversight.

At a conceptual level, classical PRA and the MPP/DES framework differ in how risk is represented. Classical PRA provides a structured representation of anticipated failure pathways through combinatorial system logic, whereas the stochastic process-based formulation represents the time evolution of system behavior from which accident occurrence emerges. In this sense, risk is not treated as a static property derived from system structure, but as a dynamic consequence of interactions among initiating events, protection availability, maintenance actions, and environmental influences over time.

This paper examines that transition, with particular emphasis on the challenges associated with adopting stochastic process-based methods and the corresponding advantages for licensing and protection system analysis. The objective is to clarify how these approaches support risk-informed, performance-based regulatory evaluation by enabling direct analysis of system behavior over time, thereby providing a more transparent and physically grounded alternative to steady-state approximations.

2 Challenges in Transitioning to MPP/DES-Based Risk Assessment

The transition from classical PRA to a stochastic process-based MPP/DES framework introduces several fundamental challenges. These challenges are not merely computational or practical; they reflect a shift in how risk is represented, quantified, and interpreted within engineering and regulatory contexts. Classical PRA captures risk as a static picture by relying on steady-state assumptions and combinatorial logic trees. MPP/DES, by contrast, models how the system actually behaves and evolves over time — a more realistic but also more demanding approach that requires richer data, greater computational resources, and more careful model design.

2.1 Computational Demands

A primary challenge of the MPP/DES approach is the increased computational burden associated with simulating time-dependent system behavior. In contrast to classical PRA, where rare-event frequencies are often approximated analytically through minimal cut-set evaluation, DES requires repeated simulation of system trajectories to estimate quantities such as ETTA distributions and exposure durations.

This challenge is particularly pronounced for rare events, where large numbers of simulation runs or specialized variance-reduction techniques may be required to obtain statistically stable estimates. As a result, computational efficiency, parallelization strategies, and convergence diagnostics become central considerations in practical implementation.

2.2 Data Requirements and Model Parameterization

The MPP/DES framework also places increased demands on data relative to classical PRA. Traditional PRA models often rely on constant failure rates and simplified representations of repair processes. By contrast, stochastic process-based models require time-dependent failure behavior, repair duration distributions, maintenance scheduling, and quantitative characterization of maintenance effectiveness.

In particular, modeling imperfect maintenance introduces the need to represent the efficacy of corrective actions, including the possibility of partial restoration or “better-than-new” outcomes resulting from root cause analysis and corrective action. Similarly, capturing dependencies across components and failure modes requires information that is often not explicitly available in standard reliability databases. These requirements necessitate integration of operational data sources, such as Computerized Maintenance Management System (CMMS) records, and may require development of new data collection and parameter estimation methodologies.

2.3 Modeling of Dependencies and System Interactions

A further challenge lies in the explicit representation of dependencies and interactions within the system. Classical PRA frequently treats component failures as independent, with dependencies incorporated through simplified constructs such as CCF models. In contrast, the MPP/DES framework requires direct modeling of interactions among components, failure modes, maintenance activities, and external hazards.

This includes treatment of common-cause influences, maintenance-induced correlations, and environmental forcing. While this capability is a major advantage, it also increases model complexity and requires careful formulation to ensure that dependencies are represented consistently and without unintended bias.

2.4 Limitations of Common Cause Failure Modeling

A central challenge in representing dependencies arises from the treatment of CCF within classical PRA and related extensions. Traditional formulations represent CCF through static probability models that implicitly assume the possibility of simultaneous failure of redundant components at the time of an initiating event. More recent simulation-based approaches [11] attempt to relax some of these assumptions, but often retain the underlying premise that multiple components may share latent failure mechanisms that persist until challenged by an initiating event.

This premise is not fully consistent with observed operational practice. In most cases, failures are identified during testing, inspection, or maintenance rather than during accident conditions. These activities

typically trigger root cause analysis and corrective actions that remove or mitigate the underlying failure mechanism before subsequent system demands. As a result, the persistence of shared failure modes across redundant components at the time of an initiating event is less likely than implied by static CCF formulations.

Even in cases where an initiating event reveals an unrecognized failure mode, it is unlikely that multiple redundant or defense-in-depth systems would be affected identically at the moment of event arrival. The time-dependent processes of failure discovery, correction, and system restoration therefore play a central role in shaping system vulnerability, but are not explicitly represented in most classical or simulation-augmented CCF models.

Within an MPP/DES framework, these effects can be represented directly by modeling the evolution of failure modes over time, including their detection, removal, and potential reintroduction. This enables a more realistic representation of dependency structures and reduces reliance on static assumptions regarding simultaneous failures.

2.5 Model Abstraction and Interpretability

The increased fidelity of MPP/DES models raises important questions regarding appropriate levels of abstraction and interpretability. Classical PRA produces relatively simple metrics, such as Core Damage Frequency (CDF), that are widely understood and easily communicated. By contrast, stochastic process-based models generate richer outputs, including distributions of outcomes and time-dependent risk measures.

Translating these outputs into forms that are meaningful for decision-making and regulatory evaluation is therefore nontrivial. It requires identification of appropriate summary metrics, visualization approaches, and reporting structures that preserve the underlying information while remaining accessible to stakeholders.

2.6 Alignment with Regulatory Frameworks

Finally, adoption of MPP/DES methods must be considered in the context of existing regulatory frameworks. Current regulatory practice is deeply rooted in PRA-based metrics and concepts, including CDF and Large Early Release Frequency (LERF). Transitioning to time-dependent risk representations requires not only technical development, but also alignment with regulatory expectations and acceptance criteria.

In particular, the use of trajectory-based risk metrics challenges interpretation of traditional frequency-based thresholds and may require development of new criteria for demonstrating adequate protection. Ensuring consistency with risk-informed, performance-based approaches such as those envisioned under 10 CFR Part 53 will be essential for practical adoption.

3 Advantages for Licensing and Protection System Analysis

Despite the challenges outlined above, the MPP/DES framework provides several important advantages for licensing and protection system analysis. These advantages arise not only from explicit representation of system behavior over time, but also from the ability to represent finite operating horizons, maintenance-driven removal of failure modes, corrective-action efficacy, and evolving dependency structures within a unified framework. In this sense, the approach is not merely a dynamic extension of PRA, but a reformulation of risk quantification around time-dependent system evolution and observable protection performance.

3.1 Time-Dependent Representation of Risk

A primary advantage of the MPP/DES framework is the ability to represent risk as a time-dependent quantity rather than as a long-run frequency. By modeling accident occurrence as a counting process derived from system state trajectories, the approach enables direct evaluation of ETTA distributions, exposure durations, and configuration-specific risk under evolving conditions.

3.2 Explicit Representation of Maintenance and Corrective Action

The MPP/DES formulation enables explicit modeling of maintenance, testing, and corrective actions as time-dependent interventions. Unlike classical PRA, where maintenance is typically represented through average availability, this approach captures the role of root cause analysis and corrective action in removing or mitigating failure modes before subsequent system demands.

3.3 Dynamic Representation of Dependencies

The framework enables dependencies to be represented as evolving system characteristics rather than static assumptions. Failure modes may be introduced, detected, corrected, and removed over time, allowing dependencies to arise and dissipate rather than persist as latent conditions.

This provides a more realistic representation of system vulnerability and reduces reliance on assumptions regarding simultaneous failures of redundant components.

This distinction is especially important for protection system analysis, where testing, inspection, and maintenance commonly reveal vulnerabilities before initiating event arrival. By treating dependency structures as time-dependent and operationally mediated, the MPP/DES approach captures an important aspect of plant behavior that is largely absent from classical PRA and only partially addressed in simulation-augmented formulations.

3.4 Evaluation of Prevention and Mitigation Tradeoffs

The time-domain formulation enables direct evaluation of tradeoffs between accident prevention and consequence mitigation. By quantifying both accident occurrence and post-accident exposure, the framework supports analysis of containment performance alongside protection-system effectiveness.

3.5 Alignment with Performance-Based Regulation

The MPP/DES framework aligns naturally with risk-informed, performance-based regulatory approaches. By focusing on observable system behavior over time, it provides a more direct and defensible basis for evaluating safety margins and demonstrating adequate protection under evolving regulatory expectations.

More specifically, the present formulation suggests that licensing analysis can be structured around quantities directly connected to performance over the relevant operating horizon, rather than inferred from long-run steady-state frequencies alone. This is important for advanced reactor applications, where regulatory attention is increasingly directed toward demonstrable safety performance, maintenance and inspection programs, and the robustness of containment and mitigation features under uncertain conditions.

4 Implications for Licensing and Containment Strategy

The transition from classical PRA to a time-domain stochastic framework has important implications for nuclear power plant licensing and the evaluation of protection system performance. These implications arise not only from improved representation of system behavior, but also from the ability to analyze directly how uncertainty, maintenance, and operational decisions influence safety outcomes over time.

4.1 From Frequency Metrics to Performance-Based Evaluation

Classical PRA expresses risk primarily in terms of long-run frequency metrics, such as CDF and LERF. While these quantities have been widely used to support risk-informed decision-making, they rely on steady-state assumptions that may obscure the influence of time-dependent system behavior and configuration-specific vulnerabilities.

By contrast, the MPP/DES framework enables direct evaluation of system performance over finite time horizons, consistent with licensing and operational decision contexts. Metrics such as ETTA, exposure duration, and conditional risk under evolving configurations provide a more direct connection between system behavior and safety outcomes. This shift supports a performance-based interpretation of risk in which safety is evaluated on the basis of observable system behavior rather than inferred steady-state properties.

4.2 Implications for Protection System Evaluation

Explicit modeling of failure modes, maintenance, and corrective action has important consequences for how protection systems are evaluated. Classical PRA formulations often treat failure probabilities as persistent characteristics of components or systems. Operational practice, however, involves continuous monitoring, testing, and maintenance activities that identify and remove failure modes before system demand.

By representing these processes explicitly, the MPP/DES framework enables evaluation of protection-system performance as a dynamic process shaped by failure discovery and corrective action. This provides a more realistic basis for assessing system reliability and supports development of performance metrics directly linked to maintenance and testing outcomes.

4.3 Reconsideration of Common Cause and Redundancy

The reinterpretation of CCF within a time-dependent framework also has implications for evaluation of redundancy and defense-in-depth. Rather than assuming persistent latent failure mechanisms affecting multiple components simultaneously, the stochastic process-based approach recognizes that such mechanisms are subject to detection and removal over time.

This perspective suggests that the effectiveness of redundancy depends not only on design diversity, but also on the processes by which failure modes are identified and corrected. As a result, licensing evaluations may benefit from greater emphasis on inspection, testing, and maintenance programs as integral components of system reliability rather than as secondary considerations.

4.4 Containment as a Dynamic Barrier to Risk

Historical experience, including the ECCS hearings [1], underscores the role of containment as a final barrier to public risk in the presence of uncertainty in protection-system performance. Within a time-

domain framework, this role can be evaluated explicitly by modeling both the likelihood of core damage and the subsequent evolution of accident conditions and containment response.

This enables analysis of tradeoffs between prevention and mitigation strategies in a unified manner. In particular, it supports a regulatory perspective in which established industry practices are relied upon for core-damage prevention, while containment systems are designed and evaluated under the assumption that core damage has occurred. Such an approach provides robustness against uncertainty in protection-system performance while maintaining consistency with defense-in-depth principles.

4.5 Alignment with Emerging Regulatory Frameworks

The capabilities of the MPP/DES framework are well aligned with risk-informed, performance-based regulatory approaches, including those envisioned under 10 CFR Part 53. By enabling direct analysis of system behavior over time, the framework supports more transparent and technically grounded evaluation of safety margins and design adequacy.

This alignment is particularly important in the context of evolving regulatory expectations and increased emphasis on demonstrable performance. By reducing reliance on simplifying assumptions and providing a clearer connection between analysis and observable system behavior, stochastic process-based methods offer a path toward more defensible and efficient licensing processes.

5 Conclusions

This paper has examined the transition from classical PRA to a time-domain stochastic framework based on MPP and DES, with particular emphasis on the challenges and advantages associated with that transition. Classical PRA has provided a valuable framework for organizing knowledge about potential failure pathways in nuclear systems, but its reliance on steady-state assumptions, static logical representations, and simplified dependency treatments limits its ability to capture the operational realities of modern plants and advanced reactors.

The MPP/DES framework addresses these limitations by representing system evolution explicitly over time, including the effects of failures, maintenance, corrective action, and external hazards. In this formulation, accident occurrence is not an intrinsic system property but arises from the interaction of initiating event arrivals and protection availability over time. This permits direct evaluation of quantities such as ETTA, exposure duration, and configuration-specific risk, while also supporting a different interpretation of failure dependency and CCF: one in which failure modes are introduced, detected, corrected, and removed through plant operations rather than assumed to persist unchanged until system demand.

Earlier work by Holmberg demonstrated the applicability of marked point processes to nuclear safety analysis, particularly in the context of living PRA and operational optimization. The present work extends that foundation by focusing on finite-horizon protection-system risk quantification and accident progression, including explicit representation of normal process termination, evolving configurations, and the effects of maintenance efficacy and corrective action on future vulnerability.

More specifically, the contribution here is to frame the transition from classical PRA to MPP/DES as a licensing-relevant finite-horizon modeling problem rather than merely as an exercise in dynamic simulation. In this setting, maintenance efficacy, root cause analysis, corrective action, and failure-mode removal are not secondary modeling details; they are determinants of future system exposure and therefore central to dependency treatment, interpretation of redundancy, and evaluation of containment and mitigation strategies.

These capabilities come with real challenges. Computational demands increase, data needs expand, and greater model fidelity raises questions of abstraction, interpretability, and regulatory implementation.

Even so, the advantages are substantial. By shifting the focus from long-run frequency estimates to time-indexed system behavior, the MPP/DES framework aligns more naturally with performance-based regulation, where maintenance histories, testing outcomes, and operating experience provide direct evidence of protection efficacy.

More broadly, stochastic process-based methods provide a different basis for evaluating adequate protection: one grounded in observable system behavior over the operating horizon rather than in inferred steady-state properties. This perspective is especially important for licensing advanced systems under evolving legal and regulatory expectations, where transparency, traceability, and physical interpretability of risk estimates are increasingly central.

A final consideration applies to both classical PRA and the stochastic process-based framework developed here. All predictive risk formulations necessarily condition on the information available at the time of analysis and therefore implicitly assume that all relevant failure scenarios are known. As shown in [12], the existence of unanticipated protection failure scenarios—whose discovery times cannot be represented within the filtration available to the analyst—introduces an unavoidable optimistic bias in computed risk metrics. This limitation is not unique to PRA, but persists in any quantification framework that relies on probabilistic characterization of future system behavior. Accordingly, while the MPP/DES formulation provides a more faithful representation of time-dependent system dynamics and maintenance-driven evolution of vulnerability, it does not eliminate the fundamental challenge associated with unknown failure scenarios. This observation reinforces the importance of defense in depth, safety margins, and corrective action programs as essential complements to quantitative risk assessment.

Future work should focus on practical implementation, including efficient rare-event simulation, improved parameter estimation from operational data, and the development of regulatory metrics that fully leverage time-domain representations of risk.

Acknowledgments

The authors acknowledge the contributions and influence of Professor Paul Nelson (Texas A&M University, deceased) and Professor Martin Wortman (Texas A&M University), whose work informed development of the stochastic analysis concepts presented in this paper.

The authors also acknowledge discussions and valuable contributions to risk analysis from Jim Liming, David Johnson, and Don Wakefield (formerly of ABS Consulting), as well as collaboration with colleagues at South Texas Nuclear Operating Company (STPNOC), particularly Alice Sun. The contributions of Vera Moiseytseva, Ph.D., through her work as an STPNOC intern and ongoing collaboration are also gratefully acknowledged.

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