A Systematic Enterprise Risk Management Framework for Modeling the Interactions of Safety and Financial Performance in Nuclear Power Plants

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Abstract: This paper reports on the advancements made by the authors to theorize and quantify the interrelationships between safety and financial performance in nuclear power plants (NPPs). The authors developed an Integrated Enterprise Risk Management (I-ERM) framework which consists of several interconnected modules for incorporating factors including human/social contributing factors, physical degradation, component reliability/availability, and plant-level availability and safety risk models to generate safety and financial risk metrics for various operations and maintenance (O&M) strategies. This paper summarizes and provides updates to the progress made in this line of research, including advancements to the I-ERM theoretical basis and methodological contributions. The theoretical advancements in this project include developing causal models related to maintenance programs and the connection between safety and financial performance of NPPs. To demonstrate the I-ERM framework, this paper provides a NPP case study.

1. INTRODUCTION

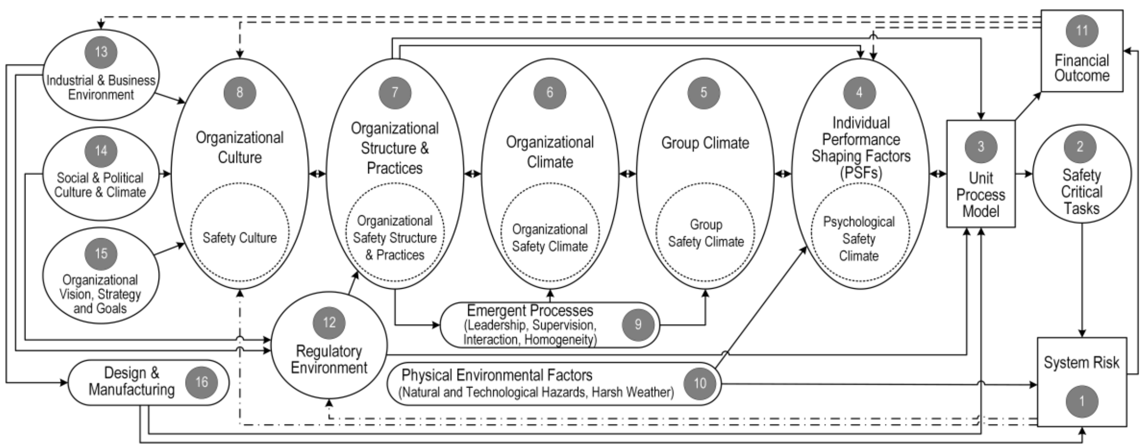
This paper reports on the progress of a Nuclear Energy University Program (NEUP) sponsored project ("Systematic Enterprise Risk Management by Integrating the RISMC Toolkit and Cost-Benefit Analysis" [1]) to develop a Systematic Enterprise Risk Management (ERM) Framework for assessing long- and short-term financial and safety risks as well as satisfying regulatory requirements for nuclear power plants (NPPs) [1]. The project is designed to provide a comprehensive framework to aid NPP decision-makers in making decisions to improve safety, cost savings and avoid production loss. The primary goal of this research is making theoretical and methodological advancements to analyze the relationships between safety and financial performance for NPPs, with explicit incorporation of maintenance performance and physical degradation. In this research, explicit incorporation of maintenance performance and physical degradation means that there are direct variables related to these two aspects within the governing equations for the phenomena of interest. The Socio-Technical Risk Analysis (SoTeRiA) theoretical framework [2] is utilized as a theoretical basis to theorize the direct and indirect relationships between safety and financial performance for complex socio-technical systems. This research expands the direct causal path from safety to financial performance in the SoTeRiA framework, as well as the indirect causal path from safety to financial performance through the development of a theoretical causal model for estimating the quality of NPP maintenance programs. Expanding the SoTeRiA framework through these two paths is a critical contribution of this research project which adds more resolution to the financial consequences of operations and maintenance (O&M) and the maintenance program quality. To operationalize the SoTeRiA framework, the authors developed an Integrated Enterprise Risk Management (I-ERM) framework to generate safety and financial performance metrics for selected O&M strategies in NPPs, which is described in this paper. This research project leveraged the development of the theoretical causal model for maintenance program quality to incorporate explicit maintenance performance modeling in the I-ERM framework, quantified using Human Reliability Analysis (HRA)-based techniques. This NEUP project also advanced the Probabilistic Physics of Failure (PPoF) analysis using spatiotemporal physics-of-failure simulations to model physical degradation that can impact safety risk and financial outcome of an NPP. The enhancement of the PPoF analysis was needed to improve the resolution of the modeling of interactions between physical degradation and maintenance performance in the I-ERM framework. The detailed description of the advanced PPoF analysis is not included in this paper but it can be found in [1, 3]. The I-ERM framework also provides a unified platform for the coupling of explicit maintenance performance and physical degradation models for the computation of safety and financial metrics. Finally, this paper reports on the implementation of the I-ERM framework for an NPP case study, in which multiple O&M strategies are considered, and time-dependent safety and financial performance metrics are computed.

This paper is structured as follows: Section 2 discusses the theoretical advancements related to the interrelationships between safety and financial performance, primarily focusing on the development of a causal model for maintenance program quality; Section 3.1 discusses the methodological developments of the I-ERM framework; Section 3.2 focuses on the implementation of the I-ERM framework for a NPP case study; and, Section 4 provides closing remarks and recommendations for the future work.

2. THEORETICAL DEVELOPMENTS ON INTERCONNECTIONS OF SAFETY AND FINANCIAL PERFORMANCE OF NPPs

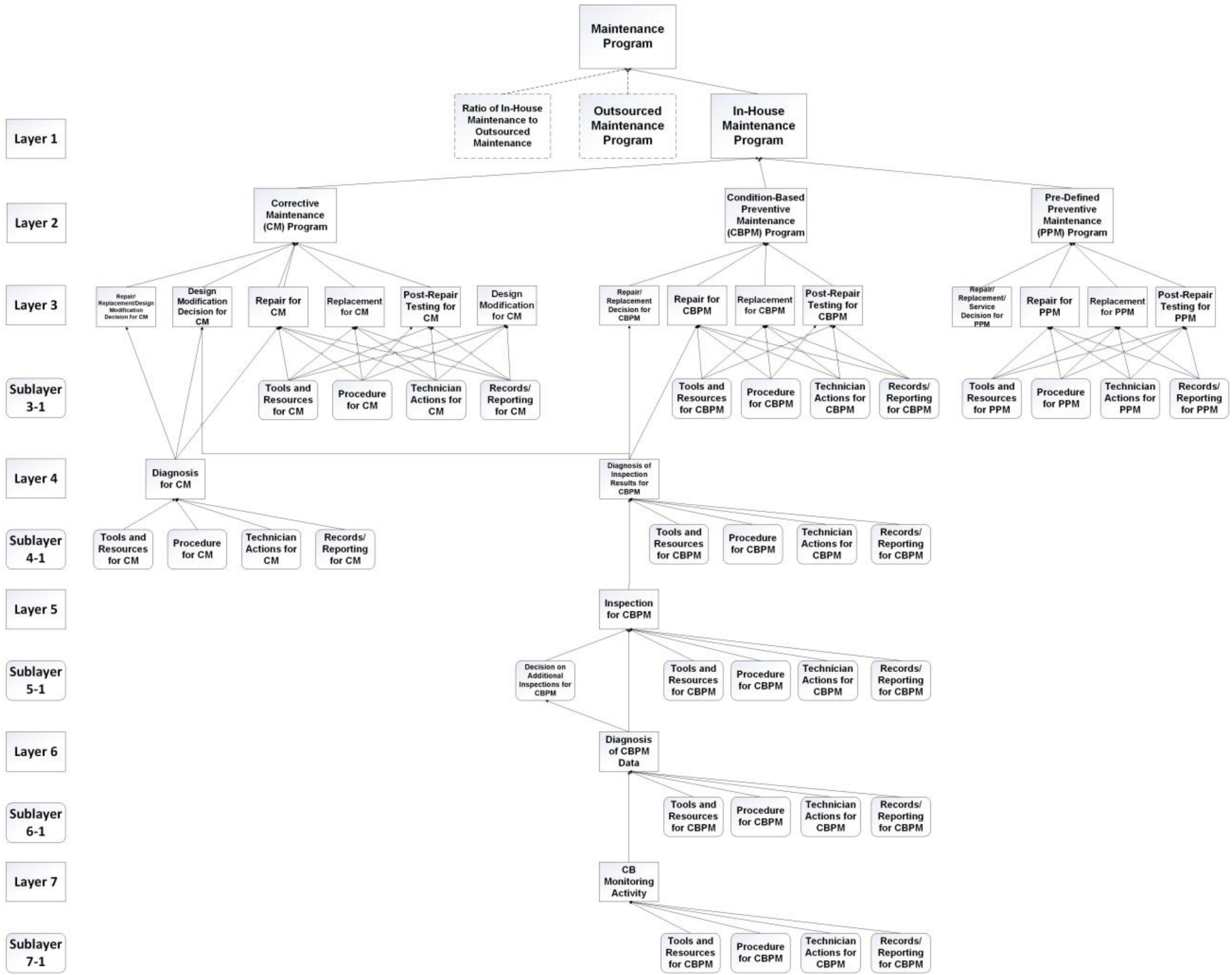
The theoretical advancements in this paper are related to building the theoretical bases for the direct and indirect relationships between safety and financial performance for NPPs. These direct and indirect relationships can be found in the SoTeRiA theoretical framework (**Figure 1**; [2]). The SoTeRiA framework connects social aspects such as the organizational culture (Node 8 in **Figure 1**) and structural features such as the organizational safety practices (Node 7 in **Figure 1**) with the system risk from PRA (Node 1 in **Figure 1**) and financial outcome (Node 11 in **Figure 1**). The SoTeRiA framework is used as a theoretical basis for the connections between safety and financial performance and specific nodes and paths are expanded in this research. This paper mainly reports on the expansion of a theoretical causal model for the performance of NPP maintenance programs, while readers are referred to the final report of the NEUP project by the authors [1] for the development of a theoretical causal model related to the direct causal path from safety to financial performance (Node 1 to Node 11 in **Figure 1**).

Figure 1: A Schematic Representation of the Socio-Technical Risk Analysis Framework and the Causal Relationships between Nodes [2]



In the NEUP project report [1], a targeted literature review of existing studies which explicitly modeled maintenance performance in the computation of safety and financial performance was conducted, and a gap analysis was performed. The literature review indicated a need for including explicit models of maintenance performance related to safety and financial performance. In this context, "explicit" incorporation of maintenance refers to those models which include maintenance parameters as input parameters to safety and financial performance models and allow for sensitivity analysis to be performed to examine the impact of those maintenance parameters on the plant safety risk and financial outcome. Among those studies which do include explicit maintenance models, a limited scope of maintenance activities were modeled and the maintenance models are quantified using a solely data-driven approach. The solely data-driven approach for maintenance model quantification is challenging in cases where the maintenance is being performed on a system with little or no operation data (e.g., advanced reactor designs), or in cases where the system has been modified (e.g., maintenance policy updates) such that the historical data is no longer relevant. To advance the solely data-driven approach for maintenance model quantification, this research proposes a model-based approach which uses a HRA-based approach to develop and quantify maintenance performance models with consideration of the relevant causal factors such as operator training and stress levels. For the model-based approach, a theoretical causal model (**Figure 2**) is developed for maintenance programs of NPPs (i.e., a maintenance unit process model in Node 3 of SoTeRiA [**Figure 1**]).

Figure 2: Proposed Causal Model for the Quality of Maintenance Programs in NPPs [1]



The development of this theoretical causal model is based on several resources, including an existing causal model for aviation maintenance performance [4], regulatory standards for NPP maintenance [5], a theory-building process from the data-theoretic methodology [6], and nuclear industry expert opinion. The target node in the theoretical causal model ("Maintenance Program" in **Figure 2**) represents the overall NPP maintenance program quality. Under the target node, seven causal layers are included which represent phases of maintenance (e.g., inspection, diagnosis, repair, and post-repair action), their associated maintenance programs, and underlying causal factors which contribute to the likelihood of successful maintenance actions for each phase of maintenance. This causal model utilizes the Structured Analysis and Design Technique (SADT) [4] to expand each maintenance phase to the direct underlying factors within sublayers. In **Figure 2**, the quality of factors in each layer is directly affected by the quality of the underlying factors in its corresponding sublayer such as the quality of resources/tools, procedures, and personnel. The causal model directs the flow of information related to maintenance program quality from the bottom of the causal model (i.e., Layer 7) to the target node. A more detailed analysis of the nodes within this causal model and their underlying factors can be found in Ref. [1]. This causal model provides analysts with significant information related to the underlying factors which contribute to the quality of specific maintenance activities and programs. The information from this causal model can be leveraged to conduct sensitivity analysis, build maintenance models for a specific maintenance program, and inform plant decision-makers to aid in prioritization of resources for O&M.

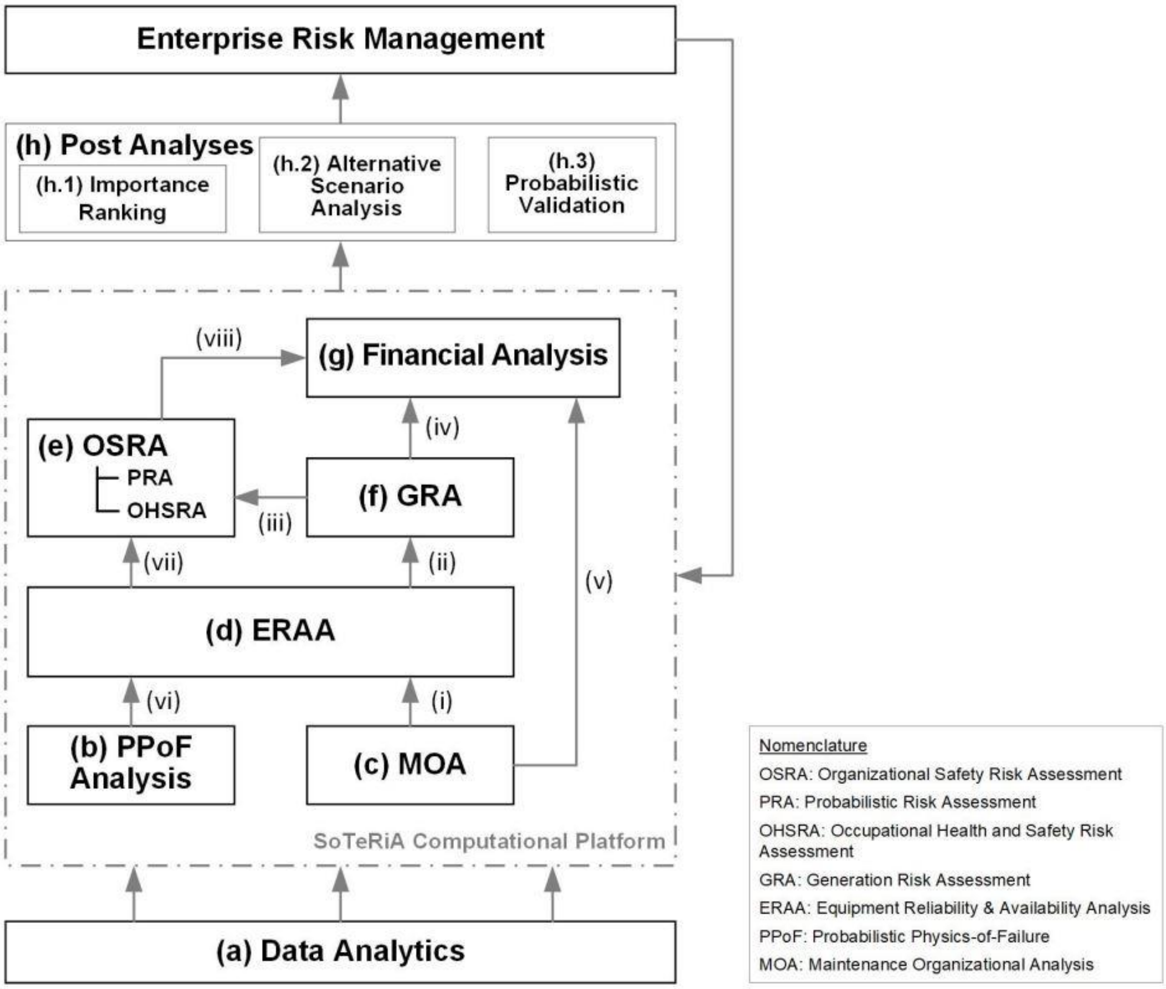
3. METHODOLOGICAL DEVELOPMENTS AND CASE STUDY

This section provides an overview of the methodological developments made to the analysis of the interrelationships of safety and financial performance, including the development of the I-ERM methodological framework. The I-ERM framework explicitly models the effects of maintenance performance interacting with physical degradation and provides a unified platform for the quantification of several nodes in the SoTeRiA theoretical framework (e.g., connections from Node 2 to 1, Node 3 to 11, Node 3 to 2, etc. in **Figure 1**). Section 3.1 provides an overview of the I-ERM framework, and Section 3.2 presents a case study implementation of the I-ERM framework.

3.1. Integrated Enterprise Risk Management (I-ERM) Methodological Framework

The I-ERM framework (**Figure 3**) is developed to provide a unified computational platform which quantifies the interconnections of safety and financial performance while explicitly incorporating the effects of maintenance work processes and physical degradation processes (and their underlying causal factors) into the safety risk and financial outcome. The I-ERM framework evaluates Organizational Safety Risk Assessment (‘e’ in **Figure 3**) with consideration of two aspects: system risk estimated using PRA and occupational safety risk assessment estimated by occupational health and safety risk assessment (OHSRA). Within the scope of this paper, the PRA module is the primary focus regarding system risk and generates estimates of plant safety risk metrics such as the Core Damage Frequency (CDF). The Financial Analysis module (‘g’ in **Figure 3**) generates short-term and long-term O&M costs of an NPP. For this research, the costs considered are maintenance labor and material costs, and production loss costs. To quantify the production loss costs, the Generation Risk Assessment (GRA) module (‘f’ in **Figure 3**) estimates the frequency of production loss events, including those events not captured in the PRA module which do not lead to severe accidents but still result in production loss.

Figure 3: Illustration of an Integrated Enterprise Risk Management (I-ERM) Methodological Framework and Interconnections between its Modules [1]



The Equipment Reliability and Availability Analysis (ERAA) module ('d' in **Figure 3**) estimates the reliability and availability inputs to the PRA and GRA modules using a renewal process model. The ERAA module takes inputs related to physical degradation and maintenance performance from the PPoF Analysis module ('b' in **Figure 3**) and the Maintenance Organizational Analysis (MOA) module ('c' in **Figure 3**) respectively. The advancement of the PPoF Analysis module is reported in Ref. [3]. The MOA module uses Human Reliability Analysis-based techniques for its quantification and structural development, while also utilizing the theoretical causal framework (**Figure 2**) discussed in Section 2 for the consideration of underlying human and organizational factors. The MOA module models maintenance scenarios using an event tree structure, where possible scenarios following the success or failure of maintenance actions are mapped to states in the renewal process model from the ERAA module. Quantification of the maintenance event trees utilizes existing regulatory standards in addition to Human Reliability Analysis-based methods such as the Integrated Human Event Analysis System (IDHEAS) [7, 8]. The model-based approach for building and quantifying the MOA module satisfies the identified need for improving the resolution of maintenance models in the calculation of safety and financial performance metrics. The Post Analyses module ('h' in **Figure 3**) includes three submodules which further assess the outputs from the I-ERM framework. Underlying human/social and physical contributing factors are ranked with respect to their impact on safety risk and financial performance using importance measure analysis [8] in the Importance Ranking submodule ('h.1' in **Figure 3**). The Alternative Scenario Analysis submodule ('h.2' in **Figure 3**) generates possible alternative O&M strategies for further analysis. The Probabilistic Validation submodule ('h.3' in

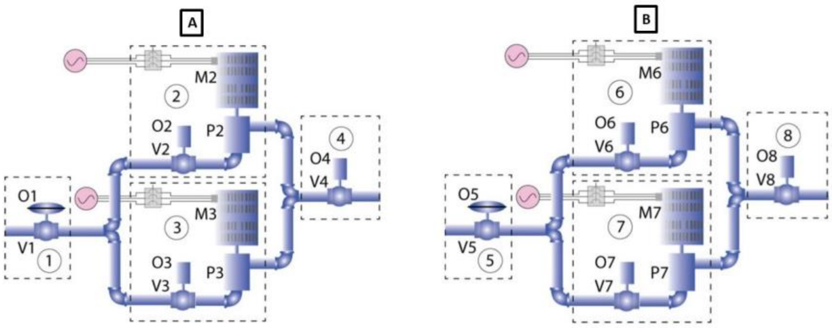
Figure 3) is used as a platform for the validation of simulation models used in the I-ERM framework and is an area of ongoing research by the authors [9, 10,11].

In addition to the development of each individual module in the I-ERM framework, the interface between several modules (labeled 'i'-'vii' in **Figure 3**) requires further analysis. One critical aspect in the development of these interfaces is the time synchronization between modules which have different timescales. As an example, the PRA module timescale is defined with respect to the PRA mission time, typically 24 hours, while the GRA and Financial Analysis modules have a timescale of one year. The integration methodology between modules provides a mathematical foundation to synchronize the timescale of information flowing throughout the full I-ERM framework. The full development of each of the interfaces is provided in Ref. [1]. Subsection 3.2 summarizes the implementation of the I-ERM methodological framework for a NPP Case Study.

3.2. Illustrative NPP Case Study

For the case study implementation of the I-ERM framework, a hypothetical NPP case study is developed which includes a production system that generates electricity outputs and a protection system which prevents severe accidents (i.e., core damage). **Figure 4** shows the protection system ('A' in **Figure 4**) and the production system ('B' in **Figure 4**), which consist of a series of pumps (P), pump prime mover motors (M), motor operated valves (V), and valve prime movers (O).

Figure 4: Illustration of NPP Case Study Consisting of a Production System and Protection System [1]



The PRA module uses system level logic models such as the combination of fault trees and event trees to compute plant safety metrics. The PRA module requires inputs related to component availability and reliability from the ERAA module (interface 'vii' in **Figure 3**) as well as system availability inputs from the GRA module (interface 'iii' in **Figure 3**). The combination of these inputs and the system-level logic is used to estimate the frequency of scenarios which result in catastrophic failure for the NPP. For scenarios which do not lead to catastrophic failure, the GRA module estimates the frequency of other scenarios which lead to production loss and other additional costs. The GRA module uses system-level modeling techniques similar to those used in the PRA module to compute the frequency, duration, and extent of production loss events using inputs from the ERAA module (interface 'ii' in **Figure 3**). Outputs from both the PRA and GRA modules (e.g., system safety metrics, frequency of specific production loss scenarios, etc.) are used as inputs to the Financial Analysis module. The Financial Analysis module measures financial performance using net value, where the net value ($NV_m^{(i)}$) is computed for each year i through the year of the expected plant lifetime (y_{plt}) and for a given maintenance strategy m among the total number of maintenance strategies (M) using the following equation:

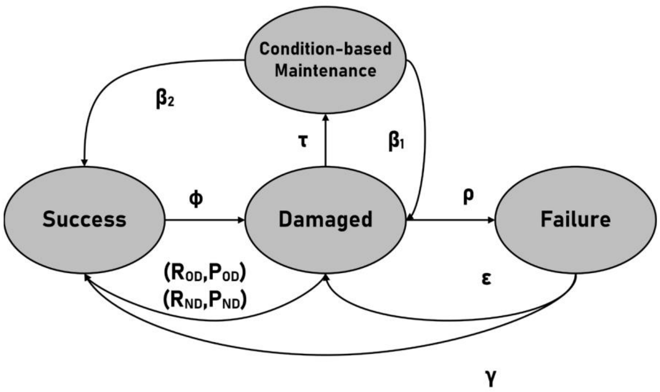
$$NV_m^{(i)} = B_{\text{Rev},m}^{(i)} - C_{\text{Ma},m}^{(i)} - C_{\text{Acc},m}^{(i)}, \qquad i = 1, \ldots, y_{plt}, \; m = 1, \ldots, M, \tag{1}$$

where the projected net value, projected revenue from electricity production ($B_{\text{Rev},m}^{(i)}$), projected costs of implementing the maintenance strategy ($C_{\text{Ma},m}^{(i)}$), and projected costs of accidents/incidents ($C_{\text{Acc},m}^{(i)}$)

are computed for each year *i* and maintenance strategy *m*. To compute the revenue and cost items in Equation 1, the Financial Analysis module requires inputs from the PRA, GRA, and MOA modules. Outputs from the Financial Analysis module are the key financial metrics which can be used to aid decision makers in the selection of O&M strategies, prioritization of resources, etc.

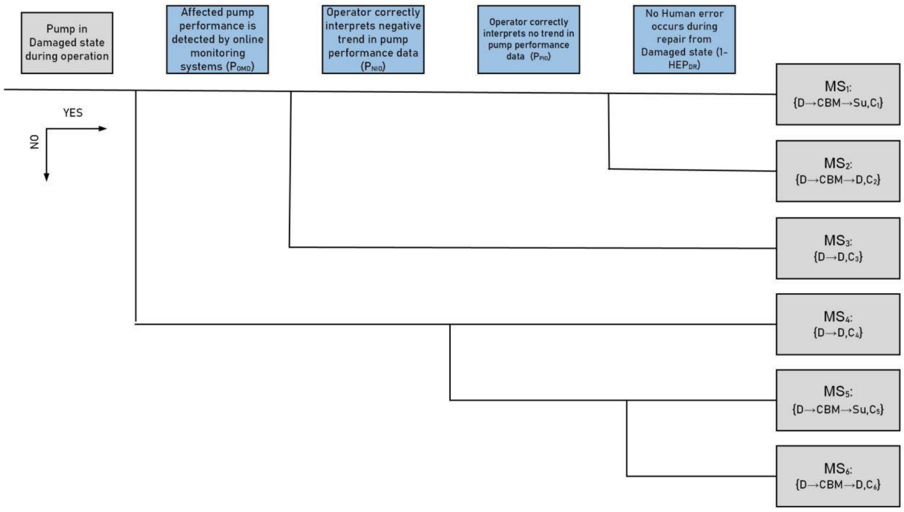
The ERAA module uses a multi-phase Markov process model to compute component reliability and availability (**Figure 5**). The component states in the Markov process model describe the functional state of the pumps ('P2' and 'P3' in **Figure 4**) of the production system, where the component may be operating normally in the "Success" state, operating in a "Damaged" state where the component has increased susceptibility to catastrophic failure, in the "Failure" state where the component does not function, or in the "Condition-based Maintenance" state where the component is free from physical degradation and may return to the "Success" state following a successful repair. The Markov process model also assumes "as-good-as-new" corrective action following repair of the component, such that the component is returned to the "Success" state following a successful repair, and the physical degradation and maintenance transition rates are assumed constant over the lifetime of the repaired component. Further research will investigate possible methods to relax this assumption, including the incorporation of effects related to root cause analysis and possible component design changes, which can lead to reduced failure rates over the lifetime of the plant. Maintenance transition rates in the Markov process model (β_1, β_2, τ, ε, γ in **Figure 5**) are generated in the MOA modules and represent the maintenance transitions, while physical degradation transition rates (ϕ and ρ in **Figure 5**) are generated in the PPoF Analysis module of I-ERM. The critical outputs from the ERAA module are time-dependent state probabilities for the four states of the Markov process model, which are used as inputs to the PRA and GRA modules.

Figure 5: Schematic Representation of a Multi-Phase Markov Process Model for Each Production System Pump [1]



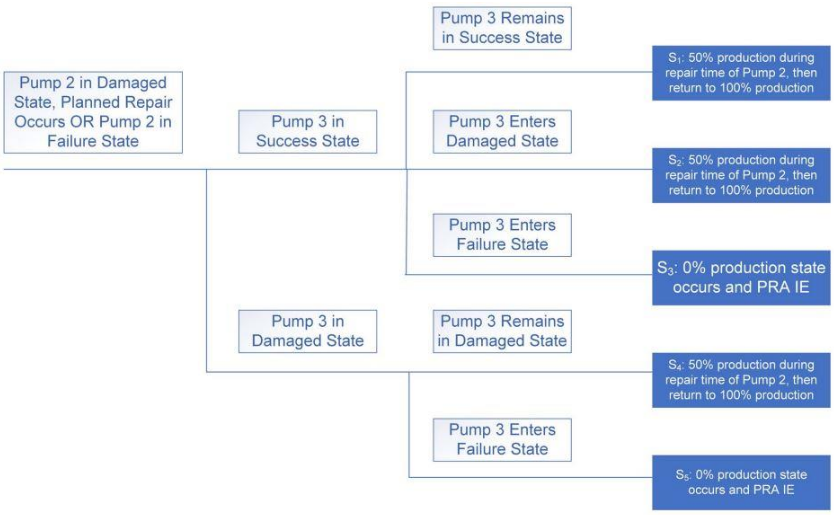
The MOA module for the case study includes models for corrective maintenance and condition-based preventive maintenance, where the model structures are designed using the theoretical causal model in **Figure 2**. The MOA module for this case study uses maintenance event trees to capture the possible maintenance scenarios associated with (i) online maintenance during reactor operation related to condition-based monitoring, and (ii) preventive maintenance during refueling outages in the form of in-service inspections. **Figure 6** shows a sample maintenance event tree related to condition-based monitoring during reactor operation, where the initial condition and end state for each maintenance scenario is related to the corresponding component states in the Markov process model (**Figure 5**). The frequencies from each maintenance scenario are computed and used to estimate the maintenance transition rates in the Markov process model. Similar maintenance event trees are developed to represent the remaining maintenance strategies and component scenarios.

Figure 6: Maintenance Event Tree for a Production System Pump for Condition-based Preventive Maintenance [1]



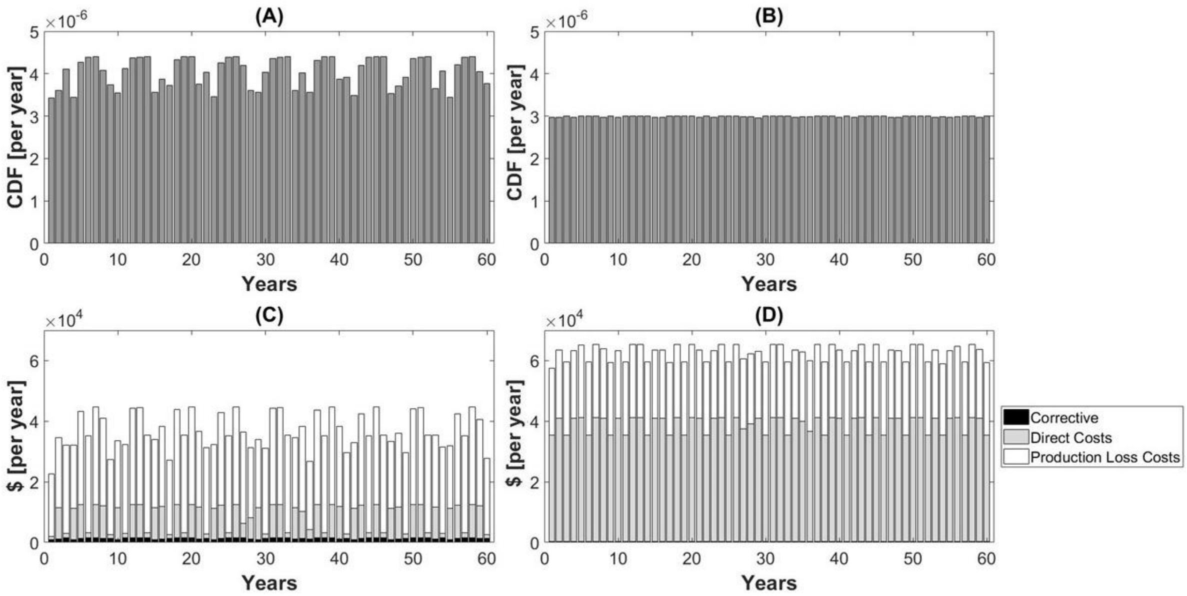
To support the interface between GRA and ERAA, GRA-ERAA Interface event trees are generated, which are used to compute the frequency of production loss scenarios from the GRA module which do not result in core damage. **Figure 7** shows a sample GRA-ERAA Interface event tree, where each scenario involves some level of production loss and some scenarios can result in a PRA initiating event. As shown in **Figure 7**, the GRA-ERAA Interface initiating events involve one componentbeing unavailable, and the resulting production state is dependent on the state of other GRA components during the unavailability of the first component.

Figure 7: Representation of a GRA-ERAA Interface Event Tree used to Estimate the Frequency of Production Loss Scenarios [1]



To demonstrate the value of the results from the implementation of the I-ERM framework, safety and financial metrics over the lifespan of the plant are computed. Two alternative cases related to the preventive maintenance strategy are considered: in the first strategy, only in-service inspection is included, while in the second strategy both condition-based preventive maintenance and in-service inspection are considered. The annual expected CDF is computed as the key safety metric from PRA, while the direct maintenance costs and production loss costs are reported as key financial performance metrics.

Figure 8: Key Expected Annual Safety and Financial Performance Metrics for a Preventive Maintenance Strategy with only In-service Inspection (Subplots A and C) and with both In-service Inspection and Condition-based Preventive Maintenance (Subplots B and D) [1]



Subplots A and B demonstrate the effect of condition-based preventive maintenance on reducing safety risk. There is a clear reduction in the expected annual CDF across the lifetime of the NPP, as well as a recued fluctuation in the CDF over time when condition-based preventive maintenance is included in the maintenance program. Subplots C and D show a stacked bar graph with the expected annual costs for each maintenance strategy and expected annual production loss costs. Subplot C shows low expected annual direct costs of maintenance, with larger contributions toward the total cost coming from expected annual production loss costs. In subplot D, we can see that the expected annual direct costs from maintenance have a much larger contribution to the total cost, while the expected annual production loss costs are reduced with the addition of the condition-based preventive maintenance program. These types of results demonstrate the value of the implementation of the I-ERM framework, where the impact of O&M program selection on the key safety and financial performance can be seen. Within the I-ERM framework, safety and financial performance metrics computed using the SoTeRiA computational platform (i.e., those modules contained within the dashed line of **Figure 2**) feed into the Enterprise Risk Management (ERM) module after conducting Post Analyses. Decision-making for O&M occurs as a part of ERM using the inputs form the SoTeRiA computational platform, where the outputs from decision-making in ERM feed back into the SoTeRiA computational platform in the form of updated O&M strategies. This approach allows the plant decision-makers comprehensive testing ability for the computation of safety and financial metrics for various O&M strategies. The model-based approach for maintenance and the synchronization between plant-, system-, and component-level models enhances the I-ERM approach for aiding in O&M decision-making when compared with existing approaches which may not include the same characteristics. Additionally, while this project did not focus on optimization, ongoing research by some of the authors investigates the development of a multi-criteria decision-making algorithm considering both safety and financial outcome [12].

4. CONCLUSION

This paper provides a summary of the recently completed research project by the authors to theorize and quantify the interrelationships between safety and financial performance for NPPs. Both theoretical and methodological advancements were summarized, including the development of theoretical causal model for the quality of maintenance programs for NPPs, the development of an Integrated Enterprise Risk Management unified platform for estimating safety and financial performance metrics, and improving the resolution of maintenance models using Human Reliability Analysis-based techniques.

Future work related to this project includes the expansion and continued development of the Probabilistic Validation submodule of the I-ERM framework. Probabilistic Validation is critical to evaluate simulation models used for the design of advanced reactors, as well as for the analysis of aging plants. Advancing the methodology for Probabilistic Validation will help to generate a platform to evaluate the validity of simulation models for future analysis. Additional future work includes the analysis of corrective actions (such as mitigation of degradation) which may occur in NPPs and relaxing the "as-good-as-new" assumption following repair. Other aspects of corrective action include root cause analysis and component redesign, which would modify the associated failure rate and/or maintenance program for the component. Future work also includes the development of a multi-criteria decision-making algorithm which considers both safety and financial outcome.

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