Toward Demonstrating the Monetary Value of Probabilistic Risk Assessment for Nuclear Power Plants

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Abstract
Inefficiencies in the operation and maintenance of Nuclear Power Plants (NPPs) have caused unnecessary shutdowns, decreases in production, and increases in system risk. Probabilistic Risk Assessment (PRA), which guides risk-informed decision-making, helps expand the operational envelope by allowing more flexibility, adding to the efficiency of preventive and corrective actions and, therefore, generates more profit. However, the financial bottom line of PRA has not yet been formally estimated. This paper reports on the current status of first-of-its-kind research for estimating the monetary value of PRA. The proposed steps for this research include: (1) developing a Generic Financial Model (GFM) to estimate the Return On Investment (ROI) that results from profit generation or cost reduction associated with a typical PRA activity in an NPP (2) implementing GFM for one of the PRA programs and validating GFM, (3) conducting uncertainty quantification for the estimated ROI from Step 2, (4) identifying existing PRA programs at an NPP (i.e., South Texas Project Nuclear Operating Company; STPNOC), (5) obtaining ROI for all the PRA activities of STPNOC, running uncertainty analysis for the total ROI, providing a probabilistic monetary value of PRA, and (6) applying importance measure and sensitivity analyses to propose improvement approaches for PRA activities.

Keywords: Probabilistic Risk Assessment, Monetary Value of PRA, Socio-Technical Risk Analysis, Financial Modeling, and Business Case for PRA

1. INTRODUCTION

For most modern industries, safety is a goal that is given the same priority as efficient and economical production and, therefore, the connection between profitability and safety has long been an issue of interest to managers, business scholars, economists, and policy makers. However, the economic gains from using Probabilistic Risk Assessment (PRA) are yet to be discovered; thus, the goal of this work is to demonstrate the monetary value of PRA, and add another layer of justification to the advantages of PRA.

1.1 Probabilistic Risk Assessment

Methods to perform quantitative risk assessment in the U.S. aerospace and missile programs were developed and improved in the early 1960s. Later, the nuclear industry used PRA as a structured and formal method for identifying and assessing risk in nuclear technological systems. In most applications, PRAs have been utilized as tools to estimate risk as a function of equipment and operator performance. The process is used to identify potential accident scenarios, estimate the likelihood and consequences of accidents, and improve system safety designs and operations. This

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analytical technique has gradually improved and been applied over the last three decades and is now an important part of risk-informed regulation. At this time, PRA has been implemented in all of the 100 Nuclear Power Plants (NPPs) in the United States.

The risk-informed regulation and licensing practices of the Nuclear Regulatory Commission (NRC) have been improving, and new opportunities are becoming available for nuclear operating companies to use PRA to prove that, in some cases, alternative decision-making does not increase risk to unacceptable levels [1, 2]. The advancement in PRA methodologies, along with NRC support of risk-informed applications has created an opportunity for NPPs to advance their use of PRA applications. The purpose of this study is to uncover a new dimension of the benefits of PRA, i.e., the monetary value that PRA brings to the nuclear industry. By demonstrating the inherent financial return of PRA, this research aims to encourage the implementation of PRA programs at NPPs.

1.2 Socio-Technical Risk Analysis

Several investigations have recognized organizational factors as root contributors to technical and operational system risk. Numerous post-accident analyses reveal an urgent need to adopt new safety culture policies in order to reduce these contributors [3,4]. Socio-Technical Risk models have evolved from Reason's "Swiss Cheese" conceptual model [5], to the more recent Socio-Technical Risk Analysis (SoTeRiA) framework, introduced by Mohaghegh [6, 7] (Figure 1). The SoTeRiA framework is a theoretical foundation [8] for integrating organizational factors (e.g., safety culture and climate, organizational structure) with PRA. Mohaghegh, Kazemi, and Mosleh also proposed a hybrid modeling technique [9] to quantify this framework. The hybrid approach [10] quantifies the interactions of organizational safety risk factors using System Dynamics (SD) and the Bayesian Belief Network (BBN), and links them to Fault Trees (FTs) and Event Trees (ETs) in technical system PRAs. Advancing the measurement of factors of the SoTeRiA framework and further operationalization of this theory is the topic of other on-going research [11].

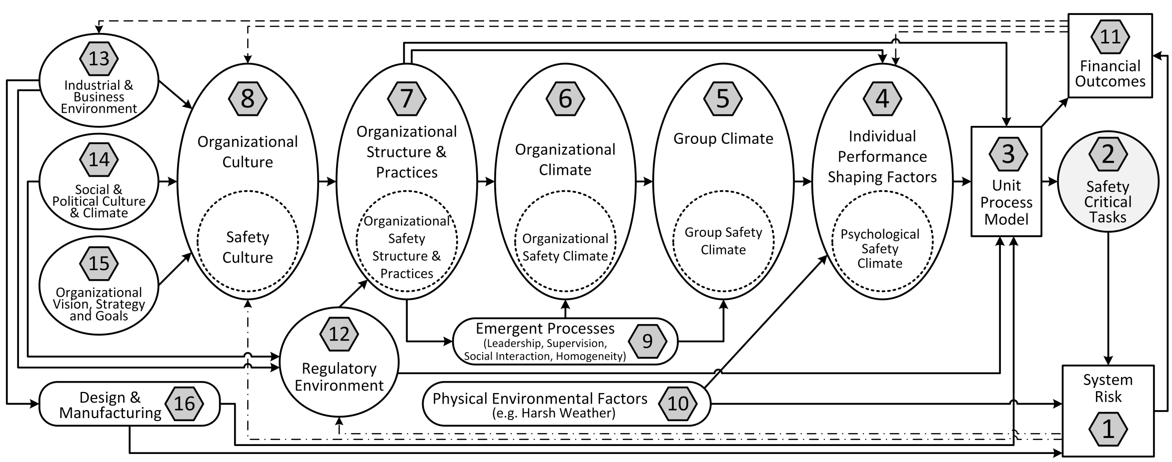

Figure 1 Socio-Technical Risk Analysis (SoTeRiA) Framework

While SoTeRiA has made a significant improvement on integrating organizational factors in technical system risk models, the relationship between "Financial Outcome" (Node 11 in Figure 1) and "System Risk" (Node 1 in Figure 1), as the two outputs of this framework, has yet to be quantified. This paper reports on the current status of on-going research that addresses the quantification of this relationship by evaluating the probabilistic monetary value of PRA. PRA-based programs at one nuclear operating company (South Texas Project Nuclear Operating Company; STPNOC) will be analyzed in order to estimate; (1) the Return On Investment (ROI) associated with PRA activities, and (2) the related uncertainties to provide a probabilistic representation of the monetary value of PRA.

1.3 System Risk and the Financial Outcome

"Risk assessment provides the ability for plant personnel to balance cost, power generation, and risk" Garrick mentions [12]. This paper reports on the current status of first-of-its-kind research for estimating the monetary value of PRA. This section summarizes the current status of the literature review related to the relationships between System Risk (Node 1 in Figure 1) and Financial Outcome (Node 11 in Figure 1). The associated literature is categorized as follows:

a. Correlations between safety and financial outcome:

i. *Correlation between system safety and profit*: Through statistical analysis, several works have attempted to find a positive correlation between safety and profitability metrics, showing that the two outputs move in the same direction, regardless of the underlying causation behind their associations. The majority of studies correlating safety and financial outcome have taken place in the transportation industries. Examining the connection between profitability and safety in the U.S. railroad industry, Golbe [13] identified a positive association between contemporaneous profit and fewer accidents over the period of one year. Alternatively, in the aviation industry, Rose [14] reported a marginally significant positive relationship between the safety-profitability of most major U.S. airlines, with a stronger positive relationship for smaller airlines. In another work, Golbe [15] states that "the sign of the relationship between profit and safety is indeterminate and depends on risk preferences," suggesting that profitability affects a firm's propensity to take risks, and that safety affects this same propensity. In the U.S. nuclear power industry, there are inconsistent conclusions about the relationship between profitability and safety. For example, Feinstein [16] examines the relationship between the financial condition and contemporaneous regulatory compliance of firms, finding no relationship between the financial strength of a utility and its regulatory violations. In contrast, Marcus et al. [17] finds that safety is weaker in less profitable utilities, where the likelihood of a significant event occurring is higher. The number of correlation-based studies on the connection between system safety and profit exceeds the scope of this paper. Madsen [18] provides more examples on this topic.

ii. *Correlation between occupational safety and profit*: Occupational safety has been extensively evaluated with respect to financial and operating profitability, in order to study the relationship between safety in the work place and the profitability of the business. Databased evaluations [19] of the relationship between occupational safety and operating performance support anecdotal evidence that good occupational safety is good for business. In other words, employees who do not feel safe in their jobs are not likely to do their jobs well; hence the economic productivity of the organization is associated with its safety conditions.

It can be concluded that empirical perspectives from different domains of research provide partial support to the safety-profitability relationship; however, no existing research addresses the connection between system risk, calculated from PRA, and the financial output of the organization.

b. Underlying mechanisms associated with the relationship between safety and financial outcome:

i. *The direct mechanisms through which system safety affects the financial outcome*: This topic refers to the impact of accidents and incidents on the financial status of organizations in high-risk industries such as nuclear, offshore oil platforms, aviation, aerospace, and healthcare. The hypothetical linkage is illustrated in Figure 1, connecting Node 1 to Node 11. The review of the literature under this topic is beyond the scope of this work, however, section 2 of the paper presents the methodology of this research, which is based on both the direct and indirect mechanisms through which system safety and financial output are connected. This method is used to develop a Generic Financial Model (GFM) in section 3.

ii. *The indirect mechanisms influencing system safety and financial outcome*: Considering the SoTeRiA framework in Figure 1, safety and financial outcome can influence each other through a multitude of indirect paths of influence. For example, the external industrial and business environment (Node 13 in figure 1) can affect the financial output of an organization when there are disruptions in the global financial market (e.g., increases in the interest rate on investment loans, sudden changes in price). The financial status of an organization can influence the propensity of managerial decision-making towards risk or safety. In other words, financial distress in the organization, caused by the external business environment, could result in managers' failure to recognize and control the trade-offs between safety and short-term economic productivity [20].

Focusing on the influence of the decision-making process on system safety, Baron and Pate-Cornell [21,22] illustrate the relationship between financial outcome and safety by analyzing the effects of alternative strategic decision-making for maintenance and operation based on long-term performance of the system. A number of other works [23,24,25] have focused on developing similar models that link managerial decision-making to system safety performance. Furthermore, as Starr and Whipple mention [26], the contingency of large financial losses due to a nuclear accident provide strong incentives for managers to focus on balancing the trade-off between system safety and economic productivity.

Post-event analyses have demonstrated the influence of financial status on managerial decision-making. For example, before the Bhopal disaster, the operations and management staff had been reduced to half in order to save money, and the refrigeration unit, which could have mitigated the gas leak, had been shut down to reduce operating expenses [27]. Kurzman [28] reported that at Bhopal, "cuts...meant less stringent quality control and thus looser safety rules. A pipe leaked? Don't replace it; employees said they were told...MIC workers needed more training? They could do with less. Promotions were halted, seriously affecting employee morale and driving some of the most skilled...elsewhere". In the analysis of the Challenger disaster, a commonly cited contributing factor was the financial pressure on NASA, and its strong connection to the social and political climate, which led to management accelerating the launch despite concerns voiced by the engineering team [29]. Further analyses [30,31] have indicated that delaying upgrades and/or maintenance operations in order to meet production goals or deadlines played an important role in the magnitude of both the Challenger accident and the loss of the Piper Alpha oil platform.

c. Impacts of organizational factors and external environment (e.g., regulatory) on the financial output of high-risk organizations: Though the following topics do not explicitly focus on the connection between safety and financial performance, the internal organizational and external environmental factors have been defined by safety method research and, therefore, are considered as categories relevant to this research:

i. *The connection between organizational factors (e.g., Node 7, 8 in Figure 1) and financial outcome (Node 11 in Figure 1):* In economics and finance, empirical studies have analyzed the relationship between a business' financial and organizational performance [32]. The findings of these studies affirm that businesses should focus on improving organizational factors (e.g., management and leadership, commitment to ethics, group culture, training, and organizational accountability) in order to achieve better results for their economic bottom line.

ii. *The connection between regulatory environment (Node 12 in Figure 1) and financial outcome (Node 11 in Figure 1):* The NRC is moving towards a proposed risk management regulatory framework, which includes PRA and risk-informed decision-making in regulatory and oversight functions [33]. One of the proposed approaches in NUREG-2150 [33] is to add cost-benefit analysis to the already existing acceptance criteria of "as low as (is) reasonably achievable" (ALARA) for risk-informed decision-making. In the consideration of costs for regulatory decision-making and to determine ALARA thresholds, regulatory analysis, Severe Accident Mitigation Alternative analysis (SAMA) [34], rulemakings, risk-informed licensing actions, and backfits are used. According to Arrow et al. [35], with limited resources to spend on regulation, cost-benefit analysis is essential, as it can help clarify the trade-offs involved in making social investments. Furthermore, most economists would argue that economic efficiency, evaluated as the difference between benefits (e.g., the value of having a safer environment) and costs (i.e., the direct expenses of policy compliance as well as the indirect costs of time and training for PRA analysts), is a fundamental measure for testing proposed environmental, health, and safety regulations; and today, cost-benefit analysis is required for all major regulatory decision making. Currently, the NRC uses three guidance documents for cost-benefit analysis, NUREG/BR-0058, NUREG/BR-0184, and NUREG-1409. Cost estimates of public exposure (dollar per person-rem) and offsite property damage are considered in the analysis to justify the cost of safety enhancements and licensing actions. The analysis guidelines in NUREG/BR-0184 consider Three Mile Island as a low estimate of exposure level and Chernobyl as a high estimate. These estimates of exposure rates and cost are based partially on the Price-Anderson Act, which determines the liability insurance estimated from public claims or property damage claims. NRC's cost-benefit analysis guidelines are being updated to reflect new determinations of consequences, probabilities and uncertainties in the existing policies.

There is great interest in using risk-informed regulation to allow more flexibility in the ways industry can reach compliance [33]. In our view, through risk-informed regulation and incentivizing PRA applications, innovations will emerge in all areas of NPP operation. For example, the Risk-Informed Asset Management (RIAM) process is where analysts review historical performance and develop predictive logic models and data analyses techniques to predict critical decision support figures-of-merit (or metrics) for managers of generating stations and electric utility company executives [36]. The RIAM metrics include (but are not limited to) profitability, projected revenue, projected costs, asset value, safety (i.e., catastrophic facility damage frequency and consequences, etc.), power production availability (i.e., capacity factor, etc.), efficiency (i.e., heat rate), etc. RIAM applies PRA techniques and generates predictions probabilistically so that metrics can be provided to managers in the form of probability distributions as well as point estimates. This application enables managers to apply the concept of "confidence levels" in their critical decision-making processes. There is an emerging list of other programs and activities that use PRA to promote the efficient functionality of a plant; risk-informed business modeling [37], on-line maintenance [38], safety assured maintenance scheduling and evaluation [39], Risk-Managed Technical Specifications (RMTS) [40], and risk-based project prioritization [41] to name a few. Significant work has been done to develop these applications, however, further research is needed to encourage the widespread use of these programs in high-risk industries.

2. RESEARCH STRATEGY

This section describes the proposed research strategy and demonstrates the necessary steps to reach the ultimate goal of determining the monetary value of PRA.

2.1 Selecting an Approach

As stated in the previous section, one method for calculating the monetary value of PRA is a purely probabilistic (correlation-based) approach that, through advanced regression analysis, finds the correlation between financial performance (as a measure of profitability and return on investment) and PRA. A statistically significant correlation would support the notion that the implementation of PRA would have a positive impact on the financial statements of the NPP operating organization. However, there are a number of deficiencies in this approach. First, due to the nature of regression analysis, finding redundant data is problematic. Secondly, due to the timelines of financial reporting, there would be a delay in the realization of the financial return on PRA programs. Finally, and most importantly, the change in the value of risk can be due to the change in the modeling approach, meaning that a change in risk does not necessarily represent a change in the real value of system risk or safety.

Considering these deficiencies, the monetary value of PRA could be redefined and looked at from another perspective. An inefficiently functioning NPP will cost more to operate, and will produce less energy. With a high frequency of component failure, an NPP will incur losses resulting from shutdowns. On the other hand, replacing and repairing the components too often will also result in a substantial increase in the cost of the operation [40]. There are various departments in an NPP carrying out different activities and programs that require an optimal financial management policy. Such a policy is cost-efficient in the way that it identifies and minimizes the associated costs and maximizes the benefits of each activity. Additionally, in complex industrial facilities such as NPPs, safety is a critical issue for decision-making; therefore, the optimal decision-making policy should consider both *financial* and *safety* factors.

The goal of this project is to show that using PRA not only advances the risk management of the NPP, but also improves the efficiency of operations and maintenance, resulting in considerable savings and added value to the economic bottom line (net earnings) of the organization. For example, in the maintenance department, events that are unimportant to safety can cause unnecessary plant shutdowns or significant resource allocations in order to determine a more reasonable Allowed Outage Time (AOT). A PRA-based program would bring more flexibility to maintenance (and operations) by expanding the operational envelope, and increasing the efficiency in estimating the times associated with surveillance frequencies, AOTs, etc., that, would help eliminate extra costs related to the deterministic methods of time estimation as well as to outage impacts. As an example, RMTS, a PRA-based program that has been implemented at STPNOC since 2007, allows the maintenance staff to exceed the front stop (or AOTs), and makes more time available to perform corrective maintenance without a significant concomitant increase in risk. This results in the prevention of unnecessary plant shutdowns that occur due to low-risk-in-service failures [42]. From this perspective, the monetary value of PRA would be the expected costs, as well as the anticipated profits generated, due to the implementation of PRA. The purpose of this research is to demonstrate that the use of insights from probabilistic risk assessment could be a significant aid in achieving risk-informed cost-efficient decision-making.

The proposed approach in this paper is an integration of *probabilistic* and *deterministic* approaches. The mechanisms and programs in an NPP that use PRA to reduce cost will be identified. In addition, the potential sources of uncertainty associated with cost saving in PRA-based programs will be identified in order to find a probabilistic monetary value of PRA.

2.2 Proposed Roadmap of the Research

The key steps in doing this research include:

1. *Developing a GFM to estimate the monetary value of a typical PRA-based activity in a nuclear power plant*: For the first step, a generic model that addresses and calculates the business return on a PRA project is developed. Considering PRA as an investment, one can calculate the ROI of PRA projects based on the modeled costs and benefits of a typical PRA activity. This model can then be modified for each PRA-based program at STPNOC and be used in later steps to evaluate the total return on PRA.

2. *Implementing the GFM for one of the PRA programs and validating the model*: Among the various PRA-based activities at STPNOC, the RMTS [40] is proposed as the basis of application for the first step of this research. The details related to RMTS are considered in order to modify GFM and to estimate the monetary return on PRA. This step aims to validate GFM.

3. *Conducting uncertainty quantification for the estimated ROI from Step 2*: All sources of uncertainty, according to the financial model, are identified and a probabilistic monetary value (ROI) of the PRA-based program of step 2 is presented.

4. *Identifying all the existing PRA programs at an NPP (e.g., STPNOC)*: The goal of PRA programs is to expand the operational envelope as widely as possible by increasing the robustness or resiliency of an operation. Therefore, such programs can bring a monetary *benefit* to the organization, in the form of profit generation or cost reduction. The maintenance and operations departments are the most likely places to implement such programs. Program examples include; RMTS, On-line Maintenance, Risk-Informed In-Service Inspections, Reactor Vessel Head Replacement [39], and RIAM.

5. *Estimating total monetary value of PRA*: This step includes obtaining the total return on PRA associated with all the PRA-based programs {i=1,…,k} identified in Step 2, running uncertainty analysis for the estimated value, and providing the probabilistic monetary value of PRA. The GFM developed in Step 1, details of each program and the associated sources of uncertainties would be considered in this step.

6. *Applying importance measure and sensitivity analyses to propose improvement approaches for PRA activities*: The total monetary value estimated in this project is based on the

current status of PRA activities at STPNOC. In implementing PRA for risk-informed decision-making, STPNOC has a very strong record of implementing successful PRA applications. Therefore, reporting the total monetary value that PRA has brought to STPNOC would be considered valuable to the industry, in order to realize the uncovered benefits of PRA that may otherwise be assumed to be expensive, luxury tools for NPPs. This derived value, however, is not the ultimate possible monetary value of PRA. Some of the PRA-based activities considered in this research might not yet have reached their maximum possible level of efficiency, and therefore, sensitivity analysis is used to present solutions for making these activities even more effective.

3. GENERIC FINANCIAL MODEL

This section explains Step 1 of the proposed approach (explained in Section 2.2.), which refers to the development of GFM. A definition for the total monetary value/return on PRA is shown as:

$$\text{Return on PRA} = ROI\_PRA = \sum \frac{Benefit_i - Cost_i}{Cost_i} \qquad (1_a)$$

{i=1,…,k} for all k PRA programs at STPNOC

The numerator in Equation 1_a, shows the Net Value of the PRA-program$_i$ and is based on the following definition:

$$NV\_PRA_i = Benefit_i - Cost_i \qquad (1_b)$$

{i=1,…,k} for all k PRA programs at STPNOC

Where **Benefit$_i$** is the monetary gain from the PRA Program$_i$, compared with not performing the program, or not implementing PRA.

Benefit$_i$ is defined as:

$$Benefit_i = Benefit_i^o + Benefit^r_i \qquad (2)$$

In Equation 2, **Benefit^o_i** refers to the Ordinary monetary gains from program$_i$. This will be specified in each program based on its functionality. There are various resources for Benefit$_i^o$. When the number of unnecessary outages is reduced, or the plant uptime is expanded, there will be both more generated profit due to a growth in the production, and fewer incurred costs due to a drop in the operation. For instance, in the GSI-191 project, more cost-savings are realized from avoiding the need for changes in the design, insulations, and outage impact. Moreover, a PRA-based program$_i$ would help prevent a number of expected risks/accidents; therefore, it reduces the costs associated with those risks. As an example, in the GSI-191 project, the risk of worker radiation exposure is reduced because of the decreased outage impact; thus, there would be monetary gains realized due to reduction or elimination of the expected costs of accidents.

Considering this explanation, Benefit$_i^o$ is regarded as the combination of growth in the production, and a decline in the expected costs. The main principle for both is the increase in the plant uptime. The expected value of the increased uptime is a function of the expected average costs associated with *support organizations* (programs) had the plant been shutdown, plus the monetary value for the expected increase in the risk, plus the growth in the production (due to increased plant uptime). Eventually, the present value of this function must be calculated, in order to get the current value of the expected Benefit$_i^o$.

$$Benefit_i^o = F\ (c_j,\ g,\ x_i^o) \quad (3)$$

$\{i=1,\ldots,k\};\{j=1,\ldots,n\}$

$\{c_1,\ldots,c_n, g\}$ = the expected average Costs, associated with support organizations, and Growth in the profit based on an increased production.

$$X_i^o = d*R_i^o \quad (4)$$

The above calculates the dollar equivalent for the expected increase in the risk. This amount is associated with the condition of not conducting the PRA-Program$_i$. For instance, the worker radiation exposure dose would be monetized here. In order to calculate X_i^o, we use the product of **d,** the dollar conversion rate, and $\mathbf{R_i^o}$, the increase in risk, both from NRC standard guidelines and STPNOC records.

$$PV\_\ Benefit_i^o = [(1-\ exp(r*t))/r]*F \quad (5)$$

This is the present value of the expected ordinary benefits associated with the PRA-program$_i$, where r is the risk-free rate of return (by definition the interest rate on a three-month U.S. Treasury Bill), and t is the time-period analysis.

Obviously, there are certain resources of uncertainty and many what-if scenarios. Uncertainty quantification will eventually present a probabilistic range for $\mathbf{PV\_\ Benefit_i^o}$, based on the expected changes in average future costs, future risk increases, and the sensitivity of the model to the dollar conversion rate. As mentioned in the previous section, this would be done in Step 5.

Returning to Equation 2, $\mathbf{Benefit^r{}_i}$ refers to the monetary gains associated with *rare* events. These gains are typically the benefits from mitigating economic impacts from severe accidents. Rare event severe accidents have expected economic/societal/human/health risks. Calculating the present value of the expected monetized impact of severe accidents provides us with the rare benefits associated with each program$_i$. To get the expected risk of severe accidents, PRA level 3 is needed, and this raises some concern due to the complexity of level 3 modeling. However, we can use generic values defined by the NRC in their standard guidelines [43].

$$Benefit_i^r = F\ (R^r{}_i) = d*R^r{}_i \quad (6)$$

$\mathbf{Benefit_i^r}$ is a function of $\mathbf{R^r}{}_i$, the expected risk of severe accident/rare event, and **d** is the dollar conversion rate. Again, calculation of the present value for the monetized rare benefits is as follows:

$$PV\_\ Benefit^r{}_i = [(1-\ exp(r*t))/r]*F \quad (7)$$

Where r can be the risk-free rate of return based on the return on US Treasury bills at the time of analysis, or it is assumed to be 7% (0.07/year) as recommended in NUREG/BR-0184. A value of 7% is conservative because cost estimates are usually performed by utilities using values between 11 and 15%. t is the time period. Time period analysis, t, can be defined based on either of the two options: the standard fiscal years at STPNOC, or the time remaining until the license term ends. Step 5 would then provide the corresponding probabilistic value.

Returning to Equation 1_b, $\mathbf{Cost_i}$ is defined as the total expenses associated with the program$_i$, which brings up equation 8:

$$Cost_i = Cost_i^p + Cost_i^b \quad (8)$$

The total cost associated with $program_i$ is the linear summation of two components: the Program Cost, and the Basic Cost. $\mathbf{Cost_i^p}$, or the program cost, refers to the costs of initiating and conducting the program. An example of this is the research cost of the project. $\mathbf{Cost_i^b}$, or the basic cost, refers to the costs of maintaining the PRA model of record at the plant or the forward cost of PRA. This basic cost includes costs such as the software license and maintenance, digital assets, and staffing labor. Financial statements of STPNOC (mainly the income statement) provide us with these amounts.
Now, the combination of Equations 1_b, 2, and 8, determines the Total Net Present Value of PRA:

$$\Sigma NV\_PRA_i = \Sigma\, Benefit_i^o + \Sigma\, Benefit_i^r - \Sigma\, Cost_i^p - \Sigma\, Cost_i^b \quad (9)$$

The focus of our research is on the monetary value of PRA; hence, the Severe Accident Benefit is assumed as $\mathbf{\Sigma\ Benefit_i^r = Benefit_{SA\_Average}}$. This is the average expected economic value of mitigating severe accidents (rare events) by conducting and implementing the PRA Programs. For the simpler calculations, this can be obtained from the NRC standard guidelines, and a generic risk value can be assumed [43]. In a similar approach, the total basic cost of PRA in the plant is defined as $\mathbf{\Sigma\ Cost_i^b = Cost_{PRA\_Average}}$. This represents the average PRA costs based on the STPNOC annual basic PRA expenses, which are related to performing basic PRA.

Rewriting Equation 9 results in:

$$\Sigma NV\_PRA_i = \Sigma\, Benefit_i^o - \Sigma\, Cost_i^p + Benefit_{SA\_Average} - Cost_{PRA\_Average} \quad (10)$$

The focus of this study is to find the return on PRA for the nuclear power plant as a complex socio-technical organization. In doing so, this research aims to uncover the positive effects of PRA on the financial statements of STPNOC. The positive effect is defined in comparison with not using PRA or not having the specific PRA-based program. This comparison narrows the focus of our model down to the first two components of Equation 10: the total Ordinary Benefits and the sum of PRA Program Costs. The Return On PRA would then be as follow:

$$ROI\_PRA = \Sigma \frac{Benefit_i^o - Cost_i^P}{Cost_i^p} \quad (11)$$

{i=1,…,k} for all k PRA programs at STPNOC

Equation 11 gives us the monetary value of PRA at STPNOC. This value is compared with the cost of not implementing PRA or not conducting the $program_i$. The uncertainty quantification, which is addressed in Step 5, will provide us with a probabilistic representation of this value.

4. CONCLUSION

This paper reports on the current status of first-of-its-kind research for estimating the monetary value of PRA. Despite existing research that shows the importance of PRA in quantifying reliable values for risk, a review of the literature highlights a gap in the assessment of financial impacts of PRA implementation in complex socio-technical systems. Therefore, it is the goal of this research to provide, through an integration of probabilistic and deterministic approaches, an estimation of financial return on PRA in order to encourage the industry to innovate and implement new PRA activities and programs.

Demonstrating monetary value of PRA will help address (1) whether we can consider system safety/risk (calculated from PRA) as a competitive advantage that adds value to a business, (2) if there is a linkage between risk/safety and the financial performance, as two important outcomes of an organization, and (3) how the risk/safety status of a complex socio-technical system (such as an NPP) affects its financial outcome.

The proposed steps for this research include: (1) developing a Generic Financial Model (GFM) to estimate the Return On Investment (ROI) that results from profit generation or cost reduction associated with a typical PRA activity in an NPP (2) implementing GFM for one of the PRA programs and validating the model, (3) conducting uncertainty quantification for the estimated ROI from Step 2, (4) identifying the existing PRA programs at an NPP (e.g., South Texas Project Nuclear Operating Company; STPNOC), (5) Obtaining ROI for all the PRA activities of STPNOC, running uncertainty analysis for the total ROI, and providing a probabilistic monetary value of PRA, (6) applying importance measure and sensitivity analyses to propose improvement approaches for PRA activities.

This paper (a) summarizes the existing literature related to a linkage between financial performance and system risk, (b) justifies the proposed integrative probabilistic- deterministic approach for this research, and (c) explains the details regarding the development of GFM, which refers to Step 1 of the proposed approach.

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