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Selecting Methodology for Developing Emergency Preparedness and Response Framework of an NPP Accident

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Abstract

The Emergency Preparedness and Response (EPR) framework to a radiological emergency in a Nuclear Power Plant (NPP) accident should be developed systematically and efficiently by applying an appropriate methodology. A systematic approach is applied in this study to select the appropriate method from different methodologies for developing EPR framework of a NPP accident by applying trade-off analysis. Ten evaluation criteria, namely causal analysis, decision making analysis, feedback analysis, interactive graphical analysis, nonlinear behavior analysis, organizational factor analysis, quantitative analysis, sensitivity analysis, statistical analysis, and threat analysis were identified for methodology selection by conducting requirement analysis of EPR framework. The System Dynamics (SD) approach was found as the most capable and the best methodologies according to the trade-off analysis by considering the assigned criteria for EPR framework of a NPP accident. The Analytic Hierarchy Process (AHP) and the Bayesian Belief Network (BBN) can also be applied in the EPR framework development process of NPP accident.

Keywords: Evaluation criteria, EPR, NPP accident, System Dynamics (SD), Trade-off analysis.

1 | Introduction

The safe operation of a Nuclear Power Plant (NPP) is essential to protect the workers, the public, and the environment. A robust Emergency Preparedness and Response (EPR) to a radiological emergency is the last level of defence in depth principle in NPP safety [1]. The three most serious accidents, Three Mile Island, Chernobyl, and Fukushima, demonstrated that the EPR framework in a nuclear emergency is a vital element of the overall safety of the plant to protect NPP personnel, emergency workers and the public beyond the site boundary [2]. The EPR framework to a radiological emergency by considering the occurrence of a severe accident of a NPP must be developed systematically and efficiently by applying a suitable methodology.

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There are many methodologies in available literature which are applied in the technical and management arena. The developing EPR framework for NPP accidents requires both the technical and management viewpoints. Thus, the formulation process of EPR framework for NPP accident is a techno-managerial approach and many criteria are required to apply during the development process of EPR framework. However, there is a lacking of systematic approach in the formulation process of EPR framework. So, the key motivation of this study is to find a suitable methodology for the formulation of an EPR framework for a radiological emergency in a NPP accident.

The systematic process is essential to select a methodology from different available methods which can handle the identified criteria for EPR framework formulation process in a viewpoint of technical management. The trade-off analysis approach is fundamental in the systematic decision making process. The trade-off matrix method can be used to come up with the best alternative option for the user to make a proper choice [3]. So, the Trade-off analysis approach can be applied to select a methodology for developing EPR framework for the occurrence of a severe accident in a NPP.

The main focus of this study is to select an appropriate methodology for developing the EPR framework to handle a radiological emergency in a NPP accident. The main objectives of this study are to conduct a brief literature review on different methodologies, to identify criteria for selection of methodology by conducting requirement analysis of EPR framework, and to select the methodology by conducting trade-off analysis on the basis of assigned criteria for developing EPR framework to a radiological emergency for NPP accident.

2 | Literature Review on Different Methodologies

The developing framework of EPR to radiological emergency in NPP is particularly important in the nuclear industry. Although the framework of EPR is developed in many NPP countries, but it is a challenge to develop EPR framework for a newcomer NPP country, in a systematized way. Thus, it is necessary to review various methodologies which can be applied in technical management area like the EPR framework.

The Analytic Hierarchy Process (AHP) is a multi-criteria decision making method with a multi-objective approach. The AHP is a theory of measurement through pairwise comparisons, and it depends on the expert judgments to derive priority scales that measure intangibles relatively [4] and [5]. It is a comprehensive method to make decisions with multi-criteria by formulating a problem as a hierarchical order [6] and it requires both quantitative and qualitative approach [7]. The AHP method has been used in the management of safety and risk management in different fields [8] and [9].

The Bayesian Belief Network (BBN) is a causal network, which is a potential technique for representing knowledge and reasoning under uncertainty [10]. It is a probabilistic graphical model which represents a system of interactive links among variables via a cause–effect relationship [11]. The BBN system consists of qualitative and quantitative parts [12] which can be applied to decision support systems with conditions of uncertainty and the sensitivity analysis can be conducted [13]. The BBN can be applied to small and incomplete data sets, structural learning framework, condition of uncertainty, and decision analysis of a complex problem [14]. A BBN provides an appropriate outline for modeling the components that affect threat with their interaction [15]. This method deals with continuous variables in a limited manner, and the model is built over the discrete domain [16].

The Failure Mode and Effects Analysis (FMEA) has proven to be a useful and powerful tool in assessing potential failures and preventing them from occurring [17]. The FMEA method is widely used to identify and eliminate known or potential failures to enhance the reliability and safety of complex systems, and it provides information for making risk-based decisions [18]. FMEA can be used in qualitative analysis and it is a structured management technique in hazard analyses [19]. It has been used as a powerful tool for risk assessment and reliability analysis in a wide range of industries [20]. However, the vague information, the relative importance ratings, and the opinion variation among experts can decrease the rationality of the results in FMEA method [21].

The Political, Economic, Socio-Cultural, Technological, Environment and Legal (PESTEL) analysis is a framework to analyze macro-environmental factors in an organization [22]. PESTEL analysis evaluates external impacts on any organization to analyze the situation and to define guidelines and directions for improving and developing a development strategy [23]. In PESTEL analysis, the evaluation of factors is performed individually, without evaluating their interaction [24]. PESTEL is generally seen as part of SWOT analysis because it examines opportunities and threats in the external environment of an organization [25].

System Dynamics (SD) is a simulation technique to frame, understand and discuss complex issues in a complicated system [26] and [27]. It is a qualitative and quantitative method with causal loop and feedback loop diagrams to formulate the inter-relations such as cause-effect relations, non-linear behavior, and dynamic changes for a complex project [28]. In a SD modeling, casual loop shows inter relations among different causes of a system while feedback loops are closed chains of cause-effect links by which more actions can be generated [2] and [29]. The SD approach generates the dynamics of a complex system by interrelating variables and actors [30]. It has been used to model strategic resource allocation, capacity building decisions, and evaluation of policy in all phases of the life cycle of disaster [31].

Strengths, Weaknesses, Opportunities and Threats (SWOT) analysis is a strategic planning framework used in evaluation of an organization, a plan, a project or a business activity [32]. SWOT analysis is generally used for analyzing internal and external dimensions in order to attain a systematic approach and support for decision making [33]. The internal dimension includes organizational factors, as well as strengths and weaknesses, and the external dimension includes environmental factors, also opportunities and threats [32]. The SWOT method helps to asses both the negative and positive influences of internal and external factors on a complex system [34] and this method can deal with disparate and disorganized ideas [35]. SWOT analysis is a user-friendly method which does not require computer modelling [36].

3 | Criteria Identification for Methodology Selection

The EPR management system is a multi-dimensional area which deals with specific circumstances in a particular emergency [37]. The developing arrangements and capabilities for EPR is one of the important elements of twenty major elements in the development of a national nuclear safety infrastructure for a national nuclear power programme in a country [38]. The developing process of EPR framework for a NPP accident requires suitable criteria in the viewpoint of technical management.

The EPR involves a number of organizations and some of these organizations play similar functions for a radiological emergency as for a conventional emergency, but a radiological emergency response requires highly specialized agencies and technical experts, and the response must be well-coordinated and arrangements must be integrated between radiological emergency and conventional emergency [39]. The infrastructural elements such as authority, organization, coordination, plans and procedures, logistical support and facilities, training, drills and exercises and quality assurance programme are required for efficient response to a radiological emergency. Besides, the allocation of functions and responsibilities in EPR are required by considering the performance of overlapping functions by several bodies namely state agencies, the government, the regulatory body, a national coordinating authority, operators and response organizations [40]. Therefore, the analysis capability of the organizational factors, systematic decision making, threat assessment, and interactive coordination among different organizations must be required for a methodology which can be applied in developing EPR framework.

During a severe accident in a NPP, thermal hydraulics parameters such as high pressure can have effects on coolant water injection to the reactor which can positively impact on the accident progression [41]. When harsh radiological conditions are detected to the public and workers, it panics and the lacking of human resources can occur to emergency response to on-site and off-site by making positive feedback on the deterioration of the emergency situation [2] and [41]. So, the analysis capability of the viewpoint of casual effect, feedback effect, and nonlinear relation among different factors for methodology involved in developing EPR framework is required.

Besides, the analysis of quantitative, sensitivity and statistical perspectives are strategically advantageous for analyzing the results of any methodology, and these criteria are also assigned in methodology selection. Thus, ten identified criteria for a methodology selection in developing EPR framework for NPP accident are shown in *Table 1* with their functional objectives.

Table 1. Identified evaluation criteria with functional objectives.

Evaluation Criteria	Functional Objectives
Causal Analysis (CA)	To identify the cause-effect relationship
Decision Making Analysis (DMA)	To make a systematic and efficient decision
Feedback Loop Analysis (FLA)	To identify feedback relationship
Interactive Graphical Analysis (IGA)	To observe dynamic coordination
Nonlinear Behavior Analysis (NBA)	To observe the trend of nonlinearity
Organizational Factor Analysis (OFA)	To identify structural influence
Quantitative Analysis (QA)	To make quantitatively correct
Sensitivity Analysis (S_nA)	To make sensitiveness correct
Statistical Analysis (S_tA)	To observe a statistical trend
Threat Analysis (TA)	To assess the threat

4 | Results

Trade-off analysis is a systematic investigation of the advantages and disadvantages of each proposed requirement approach for a system [42]. The trade-off analysis is an analytical method for evaluating and comparing system designs based on stakeholder-defined criteria. The linear method of combining data in trade-off analysis is the simplest and most commonly used method in decision making which is shown in *Eq. (1)* [43].

$$f = \sum_{i=1}^{n} w_i * x_i. \tag{1}$$

Where, f, n, w_i, x_i, are combining function in a linear weight method, total number of criteria, the normalized weight, and the score for the *i* th criteria respectively. The combining function 'f' is considered as the weighted score in this study.

In this study, it is assigned a qualitative weight on a scale from 1 to 5, to each of the 10 criteria. The assigned weight is then normalized so that the sum of the normalized weight of 10 criteria becomes 1. Based on the criteria for each alternative method, the score is allocated to each alternative. The maximum qualitative weight 5 was assigned to causal analysis and feedback analysis due to its importance to the process of EPR framework development of NPP accident. The next highest weight 4 was allocated to nonlinear behavior analysis and organizational factor analysis because these criteria play a critical role in EPR framework development of NPP accident. The weight 3 was assigned to interactive graphical analysis and quantitative analysis criteria because these factors were not very critical but required to see the analysis depth of the framework. The weight of 2 was assigned to decision making analysis because of its importance in the structural hierarchy of the model. The weight of 2 was also assigned to threat analysis because it can boost the framework. The weight of 1 was assigned to sensitivity and statistical analysis because it is possible to make these types of analysis for any framework if quantitative data is available.

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Table 2. Trade-off analysis matrix for methodology selection.

Evaluation Criteria	AHP				BBN				FMEA				PESTEL				SD				SWOT			
	Weight	Normalized Weight	Score	Weighted Score	Weight	Normalized Weight	Score	Weighted Score	Weight	Normalized Weight	Score	Weighted Score	Weight	Normalized Weight	Score	Weighted Score	Weight	Normalized Weight	Score	Weighted Score	Weight	Normalized Weight	Score	Weighted Score
CA	5	0.17	10	1.7	5	0.17	10	1.7	5	0.17	10	1.7	5	0.17	10	1.7	5	0.17	10	1.7	5	0.17	10	1.7
DMA	2	0.07	4	0.28	2	0.07	4	0.28	2	0.07	4	0.28	2	0.07	4	0.28	2	0.07	4	0.28	2	0.07	4	0.28
FLA	5	0.17	0	0	5	0.17	0	0	5	0.17	0	0	5	0.17	0	0	5	0.17	10	1.7	5	0.17	0	0
IGA	3	0.1	6	0.6	3	0.1	6	0.6	3	0.1	6	0.6	3	0.1	0	0	3	0.1	6	0.6	3	0.1	0	0
NBA	4	0.13	8	1.04	4	0.13	8	1.04	4	0.13	8	1.04	4	0.13	8	1.04	4	0.13	8	1.04	4	0.13	8	1.04
OFA	4	0.13	8	1.04	4	0.13	8	1.04	4	0.13	0	0	4	0.13	8	1.04	4	0.13	8	1.04	4	0.13	8	1.04
QA	3	0.1	6	0.6	3	0.1	6	0.6	3	0.1	6	0.6	3	0.1	6	0.6	3	0.1	6	0.6	3	0.1	6	0.6
S_nA	1	0.03	2	0.06	1	0.03	2	0.06	1	0.03	2	0.06	1	0.03	2	0.06	1	0.03	2	0.06	1	0.03	2	0.06
S_tA	1	0.03	2	0.06	1	0.03	2	0.06	1	0.03	2	0.06	1	0.03	2	0.06	1	0.03	2	0.06	1	0.03	2	0.06
TA	2	0.07	4	0.28	2	0.07	4	0.28	2	0.07	4	0.28	2	0.07	0	0	2	0.07	4	0.28	2	0.07	4	0.28
Sum				5.66				5.66				4.62				4.88				7.36				5.16

The subjective approach was used to determine the raw scores.The raw scores for each of the candidate methodologies for each evaluation were assigned as double of the assigned qualitative weight. The candidate models which do not satisfy the assigned criteria, the raw score assigned for that model is 0. The normalized weight and the allocated score are multiplied and added by making the final weighted score according to *Eq. (1)*. The results of the quantitative trade-off analysis are summarized in *Table 2*.

Comparing the weighted sums of the methodologies under considered criteria, the SD methodology scored as 7.36, which is significantly higher than the other approaches. BBN and AHP methodology scored satisfactory as 5.66 and ranked second position jointly. The SWOT methodology has acquired a score as at 5.16 and ranked as the third position. The PESTEL and FMEA methodology scored as 4.88 and 4.62 respectively.

Thus, the SD methodology is the promising methodology to be applied for EPR framework formulation process of NPP accidents. The following stages must be considered carefully to apply SD method in the EPR framework formulation process to a radiological emergency of an NPP accident: The formulation of the guidelines, procedures, regulations related to EPR to a radiological emergency; the selection of different parties to handle the radiological emergency; the identification and the allocation of roles and responsibilities of different involved parties in a radiological emergency; the determination of influencing factors of the progression of NPP accident, the assessment of the effects of radiological emergency to workers, public, and environment; the gatherings of demographic information of population surrounding the NPP site; the availability of infrastructure namely road network, transports, communication, emergency centers, and medical facilities surrounding the NPP site; and the other necessary resources to handle the radiological emergency. All of these data must be provided as input to the SD approach. After receiving all of these data, all of the criteria of the SD approach will be applied to formulate an EPR framework for a radiological emergency in an NPP accident. Finally, the EPR framework for a radiological emergency in an NPP accident will be formulated.

5 | Conclusion

This study investigates promising methodologies to be used on systematic and efficient EPR model development process of NPP accident by applying a trade-off analysis approach. For this purpose, three basic steps, namely, a brief literature review on different methodologies, an identification of evaluation criteria of these methodologies, and the selection of methodology for the developing EPR framework of NPP accident were performed.

Six methodologies namely, AHP, BBN, FMEA, PESTEL, SD, and SWOT are reviewed briefly for the formulation of the EPR framework of a NPP accident. Ten evaluation criteria such as causal analysis, decision making analysis, feedback analysis, interactive graphical analysis, nonlinear behavior analysis, organizational factor analysis, quantitative analysis, sensitivity analysis, statistical analysis, and threat analysis were identified for methodology selection by performing requirement analysis of the formulation of EPR framework of a NPP accident.

The tradeoff analysis matrix was formed by six chosen methodologies with respect to ten evaluation criteria. A qualitative weight was provided for each criteria and normalized weight was calculated. The raw scores for each of the candidate methodologies for each evaluation criteria were assigned. The normalized weight and the assigned score was multiplied and added, and the quantitative weighted score was calculated for each of the methodologies.

The SD methodology was found as the most capable and the best methodology with consideration of the criteria, and it acquired the highest weighted score. So, the SD methodology is selected as the most preferred methodology for EPR framework formulation process of NPP accident. The AHP and BBN methodology can also be used for EPR framework development process of NPP accident because these methodologies acquired the second highest weighted score. The SWOT methodology acquired the third position followed by the PESTEL and the FMEA methodologies for the development of EPR framework of a NPP accident.

In this study, only ten evaluation criteria and six methodologies were considered for trade-off analysis, which is a limitation. Further research is required in the application for SD methodology for developing the EPR framework of a NPP accident.

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