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System Dynamics Modeling for the Resilience in Nuclear Power Plants

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1. Introduction

A nuclear power plant (NPP) is classified as a safety critical organization whose safety objective is to control hazards that can cause significant harm to the environment, public, or personnel. There has been a significant improvement of safety designs as well as risk analysis tools and methods applied in nuclear power plants over the last decade.

Conventional safety analysis methods such as PSA have several limitations [1,2,3]: 1) they primarily focus on technical dimension, 2) the analysis are linear and sequential, 4) they are dominated by static models, 5) they do not take a systemic view into account, and 6) they focus primarily on why accidents happen and not how success is achieved. Hence new approaches to risk analysis for NPPs are needed to complement the conventional approaches [1].

Resilience is the intrinsic ability of a system to adjust to its functioning prior to, during, or following changes and disturbances, so that it can sustain required operations under both expected and unexpected conditions [3]. An EOS in a NPP refers to a system consisting of personnel, human-machine interface, procedures, and the interactions among these elements working together to respond to incidents.

This paper aims to model and evaluate emergency operation system (EOS) resilience using the System Dynamics. System Dynamics is the study of causal interactions between elements of a complex system. This paper identifies the EOS resilience attributes and their interactions by constructing a causal loop diagram. Then, the interactions are quantified based on literature review and simulated to analyze resilience dynamics.

2. Model of resilience in situation for Emergency Operation System (EOS)

The EOS proposed by EDF R&D is the new concept that regards many aspects of NPPs as an integrated system for the safety analysis [4]. Five key resilience attributes contributing to the resilience of EOS are suggested as shown in fig.1:

Anticipation: A resilient system must be able to anticipate both expected and unexpected events. Emergency operating procedures are the safeguards to prevent and recover from process deviations in NPPs.

Adaptation: An EOS must be able to respond to expected and unexpected threats in a flexible manner. In most cases actual situations do not match expectations and new rules are needed to recover from an incident.

Robustness: An EOS must be able to carry out the required monitoring, diagnosis, and execution functions.

Collective functioning: NPP control room crew performs the plant operational tasks collectively therefore resilience of complex system emerges in the core of collective functioning.

Learning Organization: A NPP must be able to monitor its environment for changes and learn from or adapt to these changes. Simulations, experiences from past internal and external events, telling stories by actors, and in-situation learning are some of the ways an organization can learn.

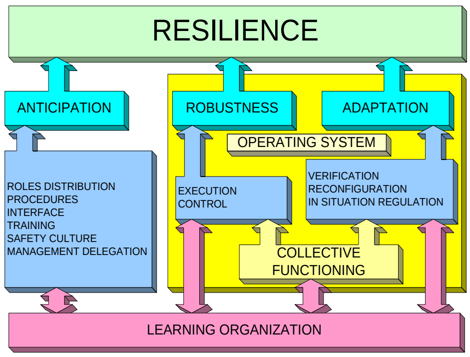

Fig.1: Model of resilience in situation (MRS) [4]

3. Modeling EOS Resilience: System Dynamics

3.1 Modeling the EOS resilience

To determine the relationships and interactions between the resilience attributes, a causal loop diagram is developed as shown in fig.2. In the diagram, the five high-level attributes of EOS affect the resilience. Then, the low-level attributes that influence the high-level are modeled. The interactions between the attributes were developed by surveying existing experimental studies, theoretical frameworks, and logical relationships from literature (however, this paper does not list all the references due to the limitation of pages). Resilience is a positive emergent property hence the influence of all the variables is amplifying (positive influence).

Learning organization and anticipation interactions are assumed to be slow acting due to time taken for the changes to be effective. Delay marks have been used to reflect this situation. The interactions of low-level resilience attributes are considered in the interaction of high-level attributes. The Vensim software, developed by Ventana Systems, is used for modeling.

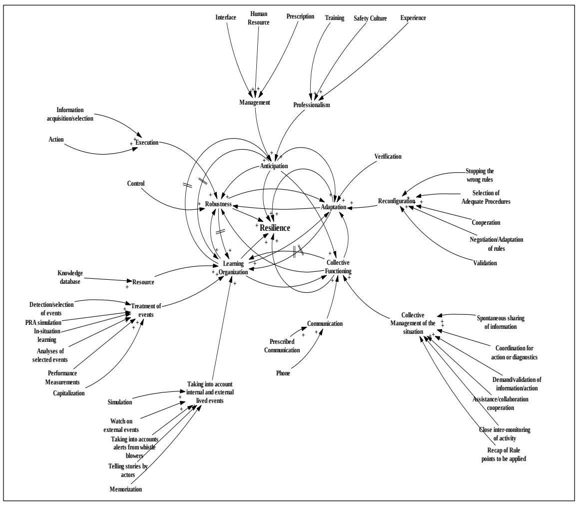

Fig. 2: Causal loop diagram for EOS Resilience

3.2 Quantification of interactions between resilience attributes

The interactions between the high-level attributes are quantified based on the number of references that explicitly demonstrate the interaction relationships. To develop the rating criteria, ninety references were used (this paper does not list all the references due to the limitation of pages). A three-point likert scale was then used to rate the interaction strengths. The rating and criteria are presented in Table 1.

Table 1: Attributes interactions rating criteria

Rating	Rating Criteria
3-points	(1) Scientific theories, research methods, conceptual models, or logical interrelationships supporting the interaction have been explicitly presented in the literature. (2) Studies/Research has demonstrated that the interaction weakness has resulted in incidents/accidents in the past. (3) Vast sources of information and data describing the interactions are available (n>20).
2-points	(1) Scientific theories, research methods, conceptual models, or logical interrelationships supporting the interaction have been explicitly presented in the literature (2) Vast sources of information and data describing the interactions are available(20<n>10))

The quantification of interactions results in Table 2. Anticipation and learning organization are assumed to be static in an emergency situation and therefore are not considered in this model.

Table 2: Attributes interactions strengths weighting table

Resilience Attributes	Anticipation	Adaptation	Robustness	Collect. Func.	Learn. Org.
Anticipation		3	2	3	
Adaptation	3		2	3	3
Robustness	2	2		2	2
Collect. Func.	3	3	2		2
Learn. Org.		3	2	2	

4. Simulation of Dynamic Behavior of Resilience

By using the System Dynamics, this approach allows simulating the dynamic behavior of resilience. The variation of resilience along with time as well as the attributes can be observed through the simulation. In addition, this approach can analyze the impact of changes in the attributes on the overall resilience.

Fig. 3 shows the dynamic behavior of resilience when the prescription and communication change by $\pm$ 20%. Due to stronger interactions between anticipation and other resilience attributes, the effect of prescription change is two times greater than that of communication.

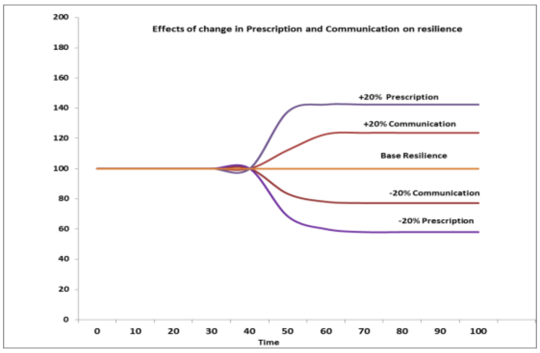

Fig 3: Effect of change in prescription and communication on resilience

5. Conclusion

This paper describes the use of system dynamics to improve understanding of the resilience dynamics of complex systems such as emergency operation systems. This paper takes into account two aspects; the strength of resilience attributes interactions and the quantification of dynamic behaviour of resilience over time.

This model can be applied to review NPP safety in terms of the resilience level and organization. Simulation results can give managers insights to support their decisions in safety management.

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