System Dynamics Modeling for Emergency Operating System Resilience

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1. Introduction

Emergency Operating System (EOS) is generally defined as a system which consists personnel, human-machine interface and procedures; and how these components interact and coordinate to respond to an incident or accident. Understanding the behavior of EOS especially personnel behavior and the factors influencing it during accident will contribute in human reliability evaluation. Human Reliability Analysis (HRA) is a method which assesses how human decisions and actions affect to system risk and further used to reduce the human errors probability. There are many HRA method used performance influencing factors (PIFs) to identify the causes of human errors. However, these methods have several limitations. In HRA, PIFs are assumed independent each other and relationship between them are not been study. In the other hand, current HRA method does not provide a causal picture of human errors. According to Mosleh and Chang [1], a causal model can provide more traceable, reproducible HRA predictions. The causal model not only provides probability of human errors but also explains the cause of it, and how we prevent those errors.

The purpose of this paper is to present a causal model which explain human error cause-effect relationships of emergency operating system (EOS) by using system dynamics (SD) approach. The causal model will further quantified by analyzes nuclear power plant incidents/accidents data in Korea for simulation modeling.

Through the SD simulation [3], users able to simulate various situation of nuclear power plant respond to emergency from human and organizational aspects. The simulation also provides users a comprehensive view on how to improve the safety in plants.

2. MRS and System Dynamics Overview

In this section, overview of Model of Resilience in Situation (MRS) and system dynamics will be discuss for basic understanding of this study.

2.1 Model of Resilience in Situation (MRS)

Électricité de France (EDF) has developed Model of Resilience in Situation (MRS) which categorizes human behavior and its relevant factors influencing EOS resilience during an event. EDF suggests five main factors that characterize the resilience of EOS: anticipation, adaptation, robustness, collective functioning and learning organization.

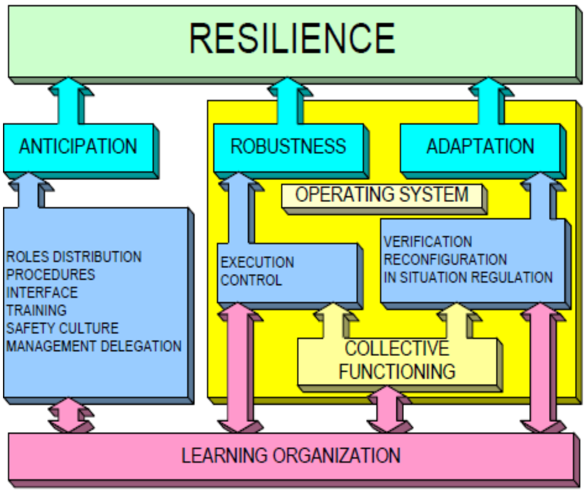


Fig.1. Model of Resilience in Situation

In order to construct a SD model, factors or variables that we want to include in the model must be first determine. Determining factors process is crucial as there are some factors are overlap in term of definition. The factors must be define separately to avoid calculation error because they are double-counted in the data. Second, factors that introduced in MRS are much more complicated and interpretation of factors relationship will become difficult.

From the list of MRS factors [4], we grouped the factors which have the same meaning and eliminate those do not have significant influence to the EOS resilience based on expert opinions. At the end, four high level factors are identified: anticipation, robustness, adaptation and collective functioning; with its twelve low level factors

2.1.1 Anticipation

Anticipation is the measure of EOS preparedness before an initiating event happens. It consists of *training*, *organization culture*, *human resource*, *human-system interface* and *system response* which expected affecting plant personnel behavior during the event.

2.1.1.1 Training

Training is associates with knowledge and experience. The utility has to be make sure the personnel are fully trained so they understand the plant conditions and able to response different emergency situation with appropriate actions.

2.1.1.2 Organization Culture

Organization culture is related to attitude, values, and beliefs of an organization toward their goal and mission [2]. Organization culture is important because it guides how organization and personnel think and act for their job. An organization which has good organization culture typically has better performance at all level.

2.1.1.3 Human Resources

Management take important roles to hire competence staff which able work in tense environment especially in emergency situation. Personnel must be able to stand with stress in emergency situation and fit in physical and psychological condition.

2.1.1.4 Human-System Interface

Human-system interface is generally defined as how personnel interact with system; and how information is delivered to operator via system. Poor designed of HIS such as bad button location, inaccessible data, and others will lead to inefficient response to event.

2.1.1.5 Procedures

During an event, personnel are asked to follow instructions based on the available procedures. Therefore, procedures must be accurate and easy to understand. A poor procedure will leads personnel to confusion and error.

2.1.2 Robustness

Robustness is applied when the current rules are effective during an event. It is the measure on how EOS determines the suitable strategic corresponding to the event and performs those actions correctly. It is composed of *system response*, *information acquisition* and *execution*.

2.1.2.1 System Response

System response can be defined as how system able to response to an event or the responses expected by personnel. For the examples, system cannot detected failure due to broken sensor, or control panel cannot responses as operator wish.

2.1.2.2 Decision Making

Decision making is refers to how personnel performs information acquisition from an event. Personnel must carefully analyze the information and determine the correct strategic corresponding to the event.

2.1.2.3 Execution

Execution is the measure on how personnel perform relevant action correctly after they decided a strategic to cope with the event. Personnel also have to continuously monitor their action if they are correctly applied.

2.1.3 Adaptation

Adaptation is applied when the current rules are no longer effective during an event. Adaptation is the measure on how EOS able to detect those operations are not adequate to current situation and carry up the new strategic. Adaptation has two aspects: *verification* and *configuration*.

2.1.3.1 Verification

Verification refer to ability of personnel to verify if current procedures to be inappropriate based on situation. Personnel must be able to identify the inadequate of actions before it leads to error.

2.1.3.2 Reconfiguration

After a strategic has been verified to be inappropriate to current situation; personnel have to switch their current actions and adapt the new actions to cope with the event. Reconfiguration describes the ability of personnel to change the new procedures based on dynamics event.

2.1.4 Collective Functioning

Collective functioning is the measure on how plant personnel work as a team to complete a task. Collective functioning addresses two major components: *communication* and *team work*.

2.1.4.1 Communication

Communication is the ability of team members to share or pass the information to each other. During an event, it is important that all the personnel have the same information of a situation. For an example, operator fails to inform his supervisor regarding the status of system failure. This will lead to major error because supervisor does not aware with the situation.

2.1.4.2 Team work

Team work is defined as a group of people works together for a common goal. In emergency situation, operators are expected to conduct different tasks respectively. Personnel must be balance in term of their workload.

2.2 System Dynamics

System dynamics (SD) is used to explore the dynamics behavior of a system over time. SD has the ability to show the interrelationship of elements within the system. It also can used to provide a clear and simple frame of a complex system and easy to be explained. The unique of SD approach is the use of feedback, stock and flow, and time delay to account for nonlinearity.

There are three main parts of system dynamics approach: causal loop diagram, stock and flow diagram and equation. Causal loop diagram is constructed to explain the interaction of variables in a system visually. Causal loop diagram was then transformed to stock and flow diagram for quantitative analysis. At last, the model built from stock and flow diagram are simulated by using computer software to explain system behavior by entering equation into the diagram.

3. Methodology

Building a SD model requires both qualitative and quantitative methods. At first, EOS factors that may include in the model must be identify. As we mentioned before in section 2.1, the factors have to be clearly defined to avoid definition confusion and sampling error. Therefore, we will used the EOS factors set in section 2.1 that already through the screening process.

3.1 Data Source

Next, Nuclear Event Evaluation Database (NEED) [6] from Operational performance Information System (OPIS) was selected for quantitative analysis. NEED was used because it contains detail information about factors that influence human error of Korea plants' event.

NEED is a database consists event history data which reported by Korea utility. It was operated by Korea Institute of Nuclear Safety (KINS) and has been upgrade to web-based database since 2002.

There are 157 events contained in NEED. Those events were analyzed by using EOS factors and coded into matrix form as shown in Table 1. Factors which contribute for the event will be coded as 1 and others as 0 as shown in Table 1.

Table 1: Sample Data from NEED

Training	Procedures	Org. Culture	Human Resource	HSI	Sys. Response	Decision Making	Execution	Verification	Reconfiguration	Communication	Team Work
0	1	1	0	1	1	0	1	0	0	0	0

3.2 Pearson's Correlation Coefficient

After the NEED is completed code with EOS factors, Pearson's correlation coefficient was used to identify the relationships between EOS factors. Pearson's correlation coefficient will gives value between +1 and -1, where +1 is positive correlation, 0 is no correlation, and -1 is negative correlation. In this study, both correlation of high and low factors were investigated. Table 2 show the correlation matrix of resilience and high level factors.

Table 2: Resilience and factors correlation matrix

	Anticipation	Robustness	Adaptation	Collective Functioning	Resilience
Anticipation	.				
Robustness	-0.12456	.			
Adaptation	0.39655	0.04730	.		
Collective Functioning	0.61236	-0.07053	0.37598	.	
Resilience	0.05929	0.76955	0.03640	0.04367	.

Table 3: High and low level factors correlation matrix

	Anticipation	Robustness	Adaptation	Collective Functioning
Training	0.46925			
Procedures	0.79300			
Org. Cultures	0.26740			
Human Resources	0.32856			
HIS	0.54547			
System Response		0.41675		
Decision Making		0.03615		
Execution		0.06730		
Verification			0.53513	
Reconfiguration			0.82825	
Communication				0.74055
Team Work				0.74055

For better understanding, all the result from Pearson's correlation has been normalized for high level factors and low level factors. Table 4 shows the normalized result for high level factors and Table 5 for low level factors. Normalized results are used to establish equation for SD model which will discuss in section 3.4. Note that anticipation is normalized below collective functioning; anticipation and collective functioning below adaptation. This is because there is relationship existed between them as shown in correlation result. Other relationships with p-value more than 0.05 [7] were omitted which can refer to Figure 2.

Table 4: Normalized correlation of high level factors

	Resilience
Anticipation	0.07
Robustness	0.85
Adaptation	0.04
Collective Functioning	0.04

Table 5: Normalized correlation of lower level factors

	Anticipation	Robustness	Adaptation	Collective Functioning
Training	0.19			
Procedures	0.33			
Org. Cultures	0.11			
Human Resources	0.14			
HIS	0.23			
System Response		0.80		
Decision Making		0.07		
Execution		0.13		
Verification			0.25	
Reconfiguration			0.39	
Anticipation			0.19	
Collective Functioning			0.17	
Communication				0.35
Team Work				0.35
Anticipation				0.30

Based on the result from Pearson's correlation coefficient, it shows that anticipation, robustness, adaptation and collective functioning factors have positive correlation with resilience. Robustness (0.76955) is main contribution to resilience, and followed with anticipation (0.05929), collective functioning (0.04367) and adaptation (0.03640).

The result also shows that anticipation and collective functioning have strong relationship (0.61236). It suggested anticipation factors such as training and safety culture, will highly impact personnel's team work and communication. Another important evidence that showed in correlation result are anticipation and adaptation (0.39655). It suggests that: perhaps with good training and procedures, personnel can easier to adapt themselves in dynamics situation. Next, there is relationship between adaptation and collective functioning with correlation 0.37598. The result shows that: team work and communication will impact on how team members share their information in situation to verify and carry out correct event mitigation strategic.

3.3 Model Development

After normalized correlations were obtained, system dynamics model that describes interrelationship between high and low level factors were constructed by using VENSIM software [5]. VENSIM is a SD simulation software to develop and analysis system dynamic models. Figure 2 shows the system dynamics model for MRS.

In SD model, the direction of the factors' relationship were draw by referring literature review and expert's judgement. From the model, each low level factor was linked to its high level factors. On the other hand, high level factors were linked to resilience. The relationship within high level factors were established for model completeness.

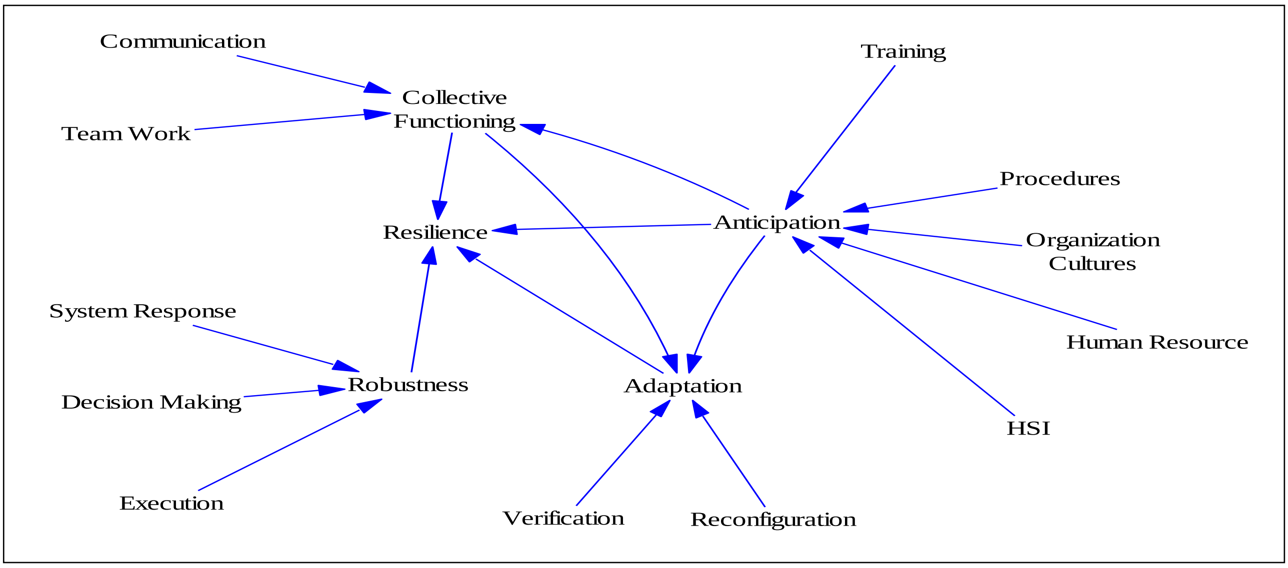
3.4 Formulation and Quantification

Quantification process is the essential part of SD modeling after the model development. The equation will be formulates and inputs into SD model for simulation. The equation was formed based on normalized correlation result. For the example:

$$\text{Resilience} = (0.07 \times \text{Anticipation}) + (0.85 \times \text{Robustness}) + (0.04 \times \text{Adaptation}) + (0.04 \times \text{Collective Functioning})$$

The equations of all factors were constructed as above by using the result from section 3.2. The initial value of the low level factors was given 100%. The assumption that all factors were in good condition at the beginning during normal situation was made.

Fig.2. MRS Causal Loop Model



4. Result and Discussion

Resilience is expected to degrade slowly over time. For the example, if training didn't perform at some time, the execution skill of personnel will decreased. In this paper, we make assumption that resilience is degraded at a rate which all the low level factors will degraded 20% from their initial condition. As we can see in Figure 3, resilience are decay because the effects from EOS factors. Korea's nuclear power plant usually carried the training for plant personnel every four months. As the Figure 3 shown, the resilience will recover to normal condition every four months. For the study purpose, 24 months were used in SD simulation.

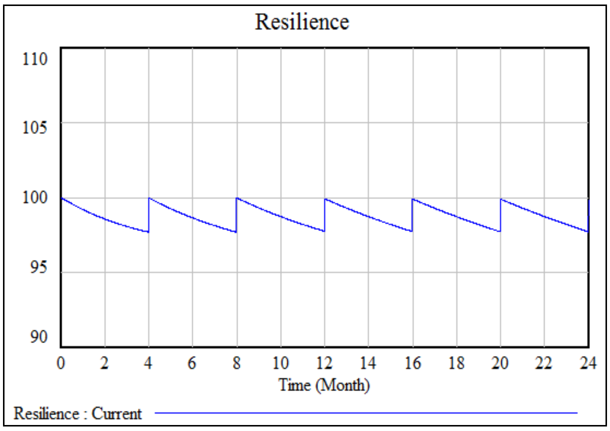


Fig.3. Effect of factors degradation to resilience

4.1 Impact of Variation of EOS on Resilience

SD model can use to predict the impact of variation of EOS on resilience over time. Figure 4 shows the impact of system response to resilience. If system response is decreased from 100% to 80%, the system lost its resilience greatly. In SD model, all kind of impact of EOS on resilience can simulated through input the value into the equation.

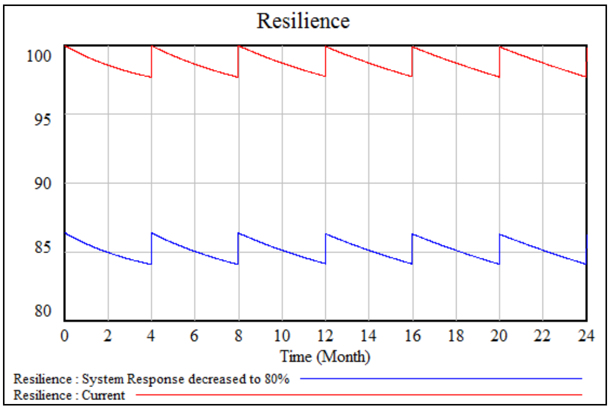


Fig.4. Impact of system response on resilience

High level factors such as anticipation and others can also investigated. Figure 5 shows if anticipation decreased to 80%, system will lose some resilience ability to about 86%. This huge change of resilience because most the event that analyzed from NEED are contributed by system response. Therefore, resilience and system response is highly correlated.

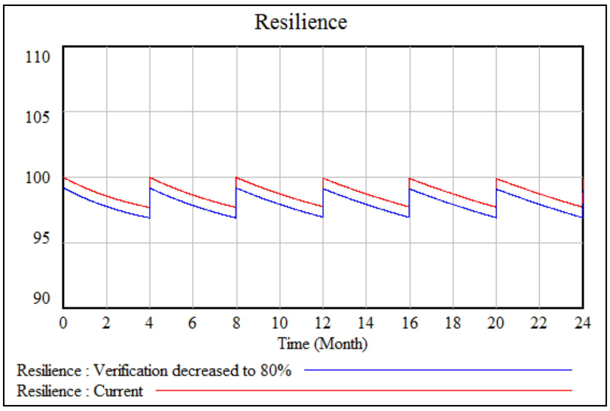


Fig.5. Impact of verification on resilience

Interaction between high level factors is another output from SD simulation. Figure 6 shows how anticipation impacts to adaptation. For the example, if anticipation decreased to 80%, adaptation also will reduced to about 95%.

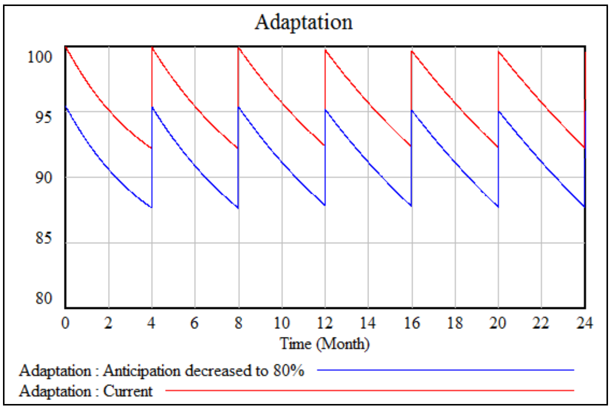


Fig.6. Impact of anticipation on adaptation

5. Conclusion

This paper presents a causal model that explained cause-effect relationships of EOS human. Through SD simulation, users able to identify the main contribution of human error easily. Users can also use SD simulation to predict when and how a human error occurs over time.

In future work, the SD model can be expanded more on low level factors. The relationship within low level factors can investigated by using correlation method and further included in the model. This can enables users to study more detailed human error cause-effect relationships and the behavior of EOS.

Another improvement can be made is on EOS factors list. Originally, EOS factors introduced by EDF were in large number and much complicated. This study was neglected some even more lower EOS factors to simplify the model. Factor analysis is suggested for the better EOS factors clarification.

Lastly, the number of sample in this study is not sufficient for SD modelling. In our analysis, we found that most the accidents were contribute by system response. In the future study, other accident data source can be refer for more reliable result.

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