Modeling the Resilience of Severe Accident Management Organizations Using AHP

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Abstract: Resilience can be defined as the intrinsic ability of a system to adjust its functioning prior to, during, or following changes and disturbances, so that it can sustain required operations under both expected and unexpected conditions. The concept of resilience in the organization of NPPs has been highlighted since the Fukushima Daiichi Nuclear Power Plant accident. An IAEA report addresses that a resilient organization is one that quickly realizes deviation from normal operations and has the ability to make even the toughest and least popular decisions and to manage the margins in which it can manoeuver.

This study attempts to model the resilience of severe accident management organizations, based on the author's previous research. First, a qualitative model of the resilience was developed for the organizational factors by reviewing emergency response plans in Korean NPP. Then, a quantitative model for entire severe accident management organizations has been developed by using the Analytic Hierarchy Process (AHP) method. For performing this method, several experts who are working on implementing, regulating or researching the severe accident management have participated in collecting the expertise on the relative importance of attributes and elements. Finally, a few simulations using the System Dynamics were conducted to discuss which factors have the most influence on resilience.

Keyword: Resilience, Severe Accident Management, Organization, and Nuclear Power Plant

1 Introduction

Resilience can be defined as 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[1]. The concept of resilience in the organization of Nuclear power plants (NPPs) has been highlighted since the Fukushima Daiichi Nuclear Power Plant accident[2]. An International Atomic Energy Agency (IAEA) report addresses that a resilient organization is one that quickly realizes deviation from normal operations and has the ability to make even the toughest and least popular decisions and to manage the margins in which it can maneuver[3]. While traditional strategy to safety in NPPs is to identify what could go or has gone wrong, the concept of resilience is focused on what the organization does well and what it does to maintain its successful operation and to capitalize on those processes in the event of an unexpected situation.

Therefore, in order to respond to a severe accident in NPPs effectively, the resilience of severe accident management organization needs to be improved by considering 1) the improvement of decision making capability and support for the decision making, 2) human factors and organizational factors in planning, execution and evaluation of training, 3) independence of regulation, 4) communication and role assignment between organizations, and 5) flexibility of adapting the organization to the situation.

This study attempts to model the resilience of severe accident management organizations, based on the Analytic Hierarchy Process (AHP)[4]. First, a qualitative model for the resilience was developed on the organizational factors by reviewing emergency response plans in Korean NPP. Then, a quantitative model for entire severe accident management organizations has been developed by using the AHP method. Several experts who are working on implementing, regulating or researching the severe accident management have participated in collecting the expertise for assigning the relative importance of attributes and elements. Finally, a few simulations using the System Dynamics were conducted to discuss which factors have most influence on resilience.

2 Characterized Resilience Model

This study uses characterized Resilience model based on the author's previous research [5]. Fig. 1 shows the structure of the Resilience model that was modified from the Électricité de France (EDF)'s resilience model. This model consists of three levels. Resilience is placed at the top. The second level contains five attributes: anticipation, robustness, adaptation, collective functioning, and organizational learning, which are characterized by their properties. Each attribute may affect the Resilience directly, and interact with the other attributes. At the third level, the elements of each attribute are defined. For the simplicity of modeling, it is assumed that elements can influence the higher attribute. Further explanation of the attributes and their elements are as follows.

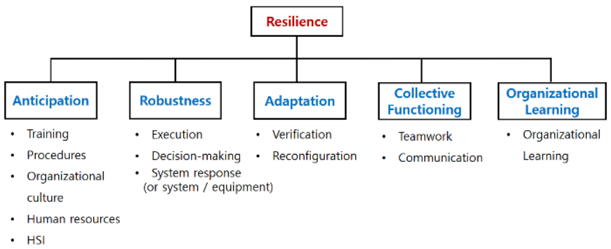

Fig. 1 The structure of the Resilience model

2.1 Anticipation

Anticipation characterizes the measures that are in place before an initiating event occurs and is, therefore, a measure of the emergency organization's preparedness before an event. Competent personnel, sufficient hardware, and good organization are required to identify issues that could become threats and then prevent the threat from occurring. Anticipation includes the NPP's emergency operation procedures, the operators' training program, and human resources, as it impacts the crew behavior in response to an initiating event.

Training refers to the knowledge and experience imparted to the personnel by the organization. Training content, scheduling, and frequency should be considered when establishing a training program. Operator training is crucial to ensuring the safe and reliable operation of NPPs. Effective training environments and systems enhance the ability of the employees to develop and maintain the competencies, (i.e., knowledge, skills, and attitudes) necessary to perform required tasks[6].

Procedures provide descriptions of the tasks that should be performed and the rules that should be followed to address specific conditions in NPPs. They provide instructions to guide operators in decision-making, and monitoring and controlling the plant and can reduce human errors[7].

Organizational Culture is related to the attitudes, values, and beliefs of an organization that support its goals and mission (e.g. safety culture). There is no universally accepted definition of safety culture. However, research studies commonly describe it as including the norms, rules, and behaviors that are presented with respect to safety, as well as the characteristics, beliefs, and values that are exhibited by an organization[8]. The most important safety culture attributes are communication, learning culture, management commitment to safety, problem identification, roles and responsibilities, and technical knowledge[9].

Human resources refer to the way that the organization hires and assigns tasks to personnel[10]. Staffing issues may cause operators to be assigned too many tasks without sufficient rest time, while inappropriate hiring decisions could lead to unqualified operators. It is an organization's duty to ensure that the operators they hire have the knowledge and ability necessary to perform their jobs, that the appropriate number of personnel are assigned to tasks, and that those personnel perform their tasks appropriately[11].

Human-System Interfaces (HSIs) include alarm systems, indicators, controllers, operator support systems, and ergonomics. HSIs are the primary mechanisms through which the personnel interact with systems during plant operation, such as instrumentation, displays, alarms, and controls. HSIs support the nuclear plant safety functions through detection, diagnosis, decision-making, and action.

2.2 Robustness

Robustness characterizes the way in which the emergency organization executes the chosen response strategy and ensures that the strategy is correctly applied. It relates to how the emergency organization determines the suitable strategy (or rules) corresponding to the event and whether it performs those actions correctly. Thus, it consists of system response, decision-making, and execution.

System Response is the measure of whether a system carries out functions as intended. The resilience of an emergency organization will be threatened if the system does not work reliably, even if an appropriate accident mitigation strategy is selected by the operators. In modern NPPs, the system response requires more emphasis because the monitoring and control tend to be automated, i.e., performed by systems.

Decision-making refers to how the personnel acquire information about the event and decide upon the appropriate action. The operator may obtain information directly from the processing system or receive processed information through an HSI. The tasks included in information acquisition are: collecting the process parameter data, organizing the information, noting the necessary information, and recognizing the required parameter values[12]. Decision-making includes the diagnosis of the plant condition and selection of the response, as guided by the Severe Accident management guidelines (SAMGs). It also includes the continuous monitoring of the feedback generated from the selected strategy and actions.

Execution is the measure of whether the personnel performs the intended actions correctly. The operators perform actions on the system through the HSI, applying the strategies or rules that were determined in the decision-making step. The primary threat to effective execution is operator error, such as mistakes, omissions, and unnecessary repetition.

2.3 Adaptation

Adaptation characterizes the way in which the emergency organization develops the strategy to cope with (adapt to) an initiating event or a change in the plant status that requires a change in the crew's response strategy. A resilient system responds to both regular and irregular threats in a robust, yet flexible manner. Actual events may not often match the expected situations, and, therefore, it is impossible to have ready-made solutions for all potential problems[13]. In case there is an unexpected event or the current strategy is not effective, the system needs to respond by adapting itself to the new situation, instead of trying to maintain stability[14]. Adaptation is the ability to detect deviations from the expected or unexpected paths and to readjust the operations accordingly[15]. In this context, adaptation consists of verification and reconfiguration.

Verification refers to the ability of personnel to verify if the current strategies, rules, or procedures are inappropriate based on the circumstances. In an severe accident situation, the MCR operators perform the tasks defined by the robustness attribute, and assess whether the present strategy is suitable to the situation, by monitoring the overall process development and alarm status, and then applying the actions that are normally provided in the NPP's SAMGs. If any discrepancy between the current situation and the goal of the strategy is observed, then the personnel need to decide whether a new strategy is required or not.

Reconfiguration describes the ability of the personnel to change the strategy or rules based on the dynamics of the event. After the current strategy or rule has been verified to be inappropriate for the current situation, the personnel need to adopt a new strategy or rule to cope with the event. The reconfiguration process involves discontinuing the application of incorrect or ineffective rules, selecting more appropriate rules, negotiating with the crew to adopt these new rules, and validating the new rules. These are performed by a person with in-situation control authority. Once the personnel decide to apply the new rules or strategy, the new rules are implemented through the activities of the robustness attribute.

2.4 Collective Functioning

Collective Functioning is the measure on how plant personnel work as a team to complete a task or achieve a common goal. The NPP control room crew members collectively perform the plant operational tasks. The resilience of complex systems such as NPPs emerges from the core of team coordination and cooperation[16]. Collective functioning is comprised of two major components in this study: communication and teamwork.

Communication refers to how the crew communicates within the shift (including with the field operators) or between shifts. Communication the means of exchanging information between individuals during group activities, and is a prerequisite for good teamwork because it establishes a shared mental model[17]. Communication is the cornerstone of teamwork, and it becomes particularly critical during abnormal and emergency conditions.

Teamwork refers to how a group of people works together to achieve a common goal. Teamwork defines how the operators interact with each other to exchange information, coordinate actions, and maintain social order[18]. Teamwork in an emergency involves the spontaneous sharing of information among team members, coordination of actions or diagnostics, validation of information or action with others, collaboration, cooperation, coordinated monitoring of activity, and a recap of the rules to be applied.

2.5 Organizational Learning

Organizational learning refers to the process in which the organization creates new knowledge or modifies existing knowledge. The effectiveness of learning from experience depends on which events or experiences are considered, as well as on how the events are analyzed and evaluated.

3 Development of the Resilience Model

3.1 Qualitative Resilience Model

This section describes how the resilience model of severe accident management organization was developed. A review of emergency response plan in Korean NPP was carried out to obtain the relationship between organizations, based on the characterized resilience model in Fig. 1.

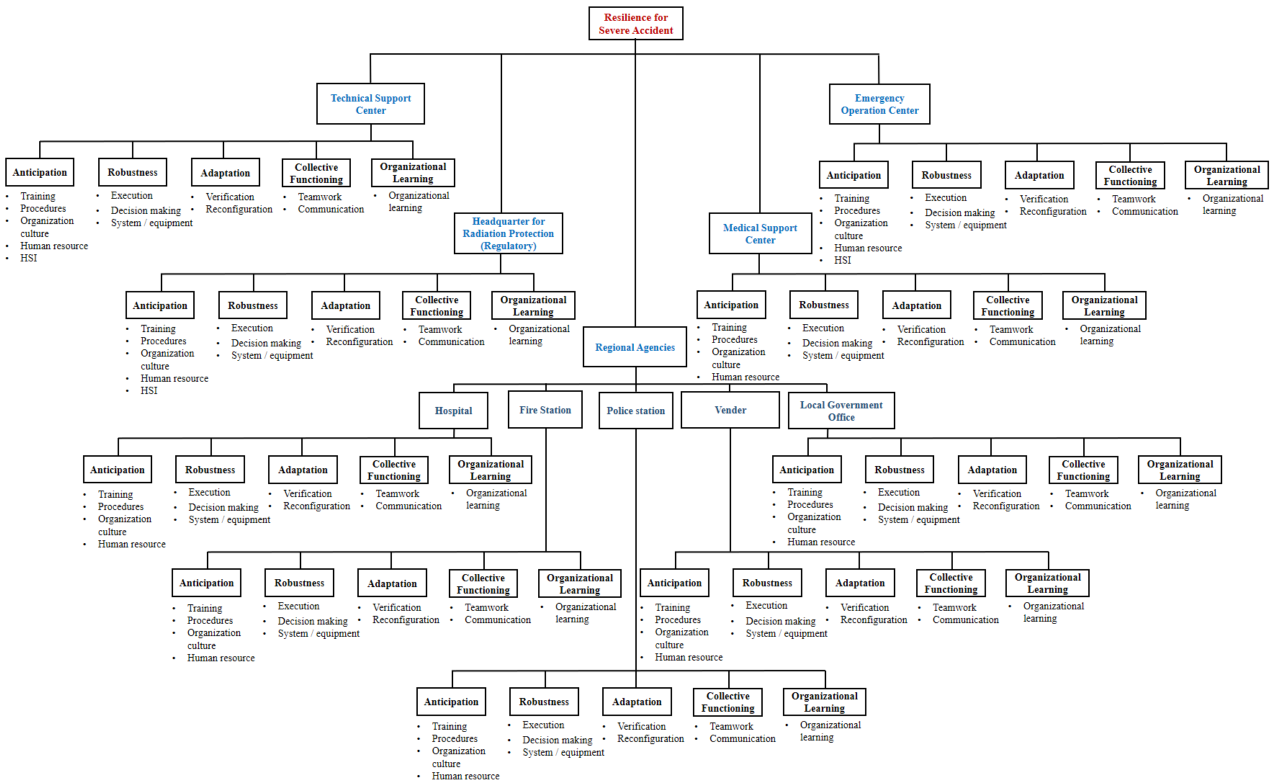

Fig. 2 Qualitative Resilience Model for severe accident management organization

Fig. 2 shows a qualitative model of the resilience with severe accident management organizations. In the model, five representative organizations that play important roles in the management of severe accident are considered as the following:

- Headquarter for Radiation Protection (Regulatory): command and control of all the severe accident management organizations
- Emergency Operation Center (Utility): execution of on-site mitigating action, preventing magnification of the accident, measuring radiation protection, and evacuation of in-site staffs
- Technical Support Center: technical support for radioactive disaster control and management
- Medical Support Center: central support of medical services for casualties as a result of exposure to harmful radiation
- Regional Agencies: local agencies to minimize the injury of citizen from the radioactive disaster, such as local government office, police station, and fire station.

3.2 Quantitative Resilience Model

A quantitative model for the entire severe accident management organizations has been developed by using the AHP method[4]. The AHP has been used as an effective tool for dealing with complex decision making, and may help the decision maker set priorities and make the best decision. Through a series of pairwise comparisons by a questionnaire, it makes weighting or ranking of importance, and helps to reflect both subjective and objective aspects of a comparison target. The AHP is considered a proper approach to quantifying the importance of elements in the model due to the lack of actual data.

Prioritization using the AHP was performed within three levels, i.e., 1) severe accident management organizations, 2) attributes in an organization, and 3) elements in an attribute. Fig 3 shows an example of questionnaire for determining priorities and calculating weighting-values between severe accident management organizations.

A	A is more important than B <----------------				Equal	B is more important than A ---------------->				B
	Very much	Moderate	A little	Not at all		Not at all	A little	Moderate	Very much	
Technical Support Center	④	③	②	①	⓪	①	②	③	④	Headquarter for Radiation Protection
Technical Support Center	④	③	②	①	⓪	①	②	③	④	Emergency Operation Center
Technical Support Center	④	③	②	①	⓪	①	②	③	④	Medical Support Center
Technical Support Center	④	③	②	①	⓪	①	②	③	④	Regional Agencies
Headquarter for Radiation Protection	④	③	②	①	⓪	①	②	③	④	Emergency Operation Center
Headquarter for Radiation Protection	④	③	②	①	⓪	①	②	③	④	Medical Support Center
Headquarter for Radiation Protection	④	③	②	①	⓪	①	②	③	④	Regional Agencies
Emergency Operation Center	④	③	②	①	⓪	①	②	③	④	Medical Support Center
Emergency Operation Center	④	③	②	①	⓪	①	②	③	④	Regional Agencies
Medical Support Center	④	③	②	①	⓪	①	②	③	④	Regional Agencies

Fig. 3 An example of questionnaire on severe accident management organizations

Six experts who are working for a wide range of professionals in the nuclear industry have participated in collecting the expertise for assigning relative importance of elements in the model. Table 1 represents expert's personal information.

Table 1 Expert's personal information

	Field of research	Organization
1	Human Factor Engineering & Probabilistic Safety Assessment	Professor
2	Social Science	Professor
3	Radiation Protection	Senior researcher (Utility)
4	Human Factor Engineering and Instrument & Control	Senior researcher (Research Institute)
5	Radiation Prevention	Senior researcher (Utility)
6	Human Factor Engineering and Instrument & Control	Senior researcher (Regulatory)

As a result, Fig. 4 shows the quantitative resilience model for the severe accident management organizations.

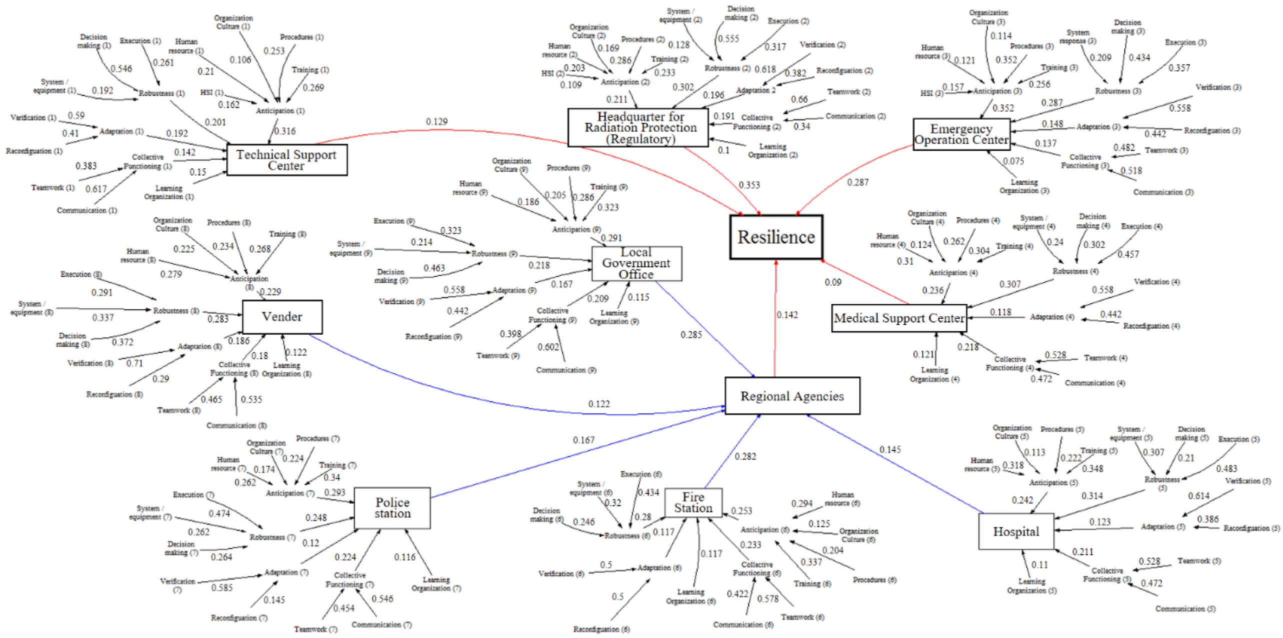

Fig. 4 Quantitative Resilience Model for severe accident management organization

4 Sensitivity Analysis on the Resilience Model

System Dynamics has been applied to quantitative resilience model for the severe accident management organizations to discuss which elements are most influencing on the resilience. Table 2 shows the result of sensitivity analysis on the resilience model.

Table 2 The result of sensitivity analysis

Rank	Elements
1	Decision making of Headquarter for Radiation Protection
2	Teamwork of Headquarter for Radiation Protection
3	Verification of Headquarter for Radiation Protection
4	Decision making of Emergency Operation Center
5	Procedure of Emergency Operation Center
6	Learning organization of Headquarter for Radiation Protection
7	Execution of Headquarter for Radiation Protection
8	Execution of Emergency Operation Center
9	Reconfiguration of Headquarter for Radiation Protection
10	Training of Emergency Operation Center

The result of sensitivity analysis indicates that the decision making of Headquarter for Radiation Protection is the most important element for the resilience of severe accident management. Teamwork and Verification of Headquarter for Radiation Protection were also identified as the second and third importance elements, respectively. In conclusion, Headquarter for Radiation Protection and Emergency Operation Center were the important organizations, as shown in Table 2.

5 Conclusion

This study aimed to model the resilience of severe accident management organizations using the AHP. First, by reviewing emergency response plans in Korean NPP, a qualitative model for the resilience was developed for the organizations who participate in the severe accident management. Then, a quantitative model for the severe accident management organizations has been developed by using the AHP method. Six experts who are working on implementing, regulating or researching the severe accident management have participated in collecting the expertise for the relative importance of attributes and elements. Finally, a few simulations using the System Dynamics were conducted to discuss which factors are most influencing the resilience. The result of sensitivity analysis indicates that the decision making of Headquarter for Radiation Protection is the most important element for the resilience of severe accident management.

This study suggests relatively new approach for managing severe accident with systemic perspective of participating organizations, which can complement conventional probabilistic safety assessment and deterministic safety analysis. This study also represents an on-going effort to consider 1) different data source (e.g., experimental and training data) and 2) how much each element of emergency organization affects the value of resilience based on a broad range of literature survey. Finally, this research is expected to be used as a starting point for evaluating the integrity of severe accident management in Korean NPPs.

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