Measuring the Resilience for the Human Reliability of Group in Multi-Unit Nuclear Power Plants

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Abstract: The human reliability analysis (HRA) of multi-unit nuclear power plant (NPP) has been made as the research hotspot after the occurrence of the Fukushima accident. However, the existing HRA method was not entirely applicable to the analysis of human reliability of group in multi-unit NPPs. On the one hand, there have been additional opportunities for human and organizational errors due to the additional complicated inter-unit organizational interactions, but the existing HRA method typically considers the organizational error as only one of the factors affecting human errors, with limited research on the evaluation of reliability for organizations with inter-unit interactions. On the other hand, the additional complicated unit-to-unit interactions might introduce risks, but instead, could help to promptly detect the occurrence of human errors in some cases, ensuring the persistence or recovery ability of system's performance under emergency. The concept of resilience has been used in research to describe this characteristic of a system. For this reason, this study proposed a simplified model to analyze the group reliability in multi-unit NPPs following the key characteristics of inter-unit sharing and collaborations, and then presented a framework to measure the resilience of group reliability in an emergency. Preliminary study has shown that in terms of the unit suffering more severe damage, inter-unit collaboration can effectively make the group more resistive to an emergency and enhance the recovery rapidity, timely resource sharing between units can effectively offset the loss of group reliability and enhance the site-level resilience.

Keywords: Resilience, Human reliability of group, Multi-unit nuclear power plants.

1. INTRODUCTION

Since the Fukushima Daiichi accident, there has been an emphasis on the risk resulting from multi-unit nuclear power plant (NPP) accidents, and the interest in human and organizational factors, which significantly contribute to the safety and reliability of multi-unit NPP, has significantly increased in the past few years [1]. According to all the multi-unit licensee event reports that were submitted to the NRC from 2000 to 2011, it has been found that the most common cause of multi-unit NPP events were human and organizational errors, accounting for 44% [2]. Although human and organizational factors affected the independence between multi units significantly, related research was still in its early stages.

The existing human reliability analysis (HRA) method was not entirely applicable to the analysis of human reliability of group in multi-unit NPPs [1]. The first question was that due to the introduction of complicated inter-unit organizational interactions, there have been additional opportunities for human and organizational errors in multi-unit NPPs, but the existing HRA method generally treats the organizational error as only one of the performance shaping factors affecting human errors. Research that focused on the evaluation of the reliability for organizations with inter-unit interactions was still limited [3-4]. More importantly, the additional complex unit-to-unit interactions might introduce risks, but instead, could also help to promptly detect the occurrence of human errors in some cases. This mechanism could guarantee the resistance or recovery ability of system's performance in an emergency. The concept of resilience has been introduced to describe such ability of system [5-6]. Therefore, it is important to understand the mechanism of inter-unit interactions on the organizational reliability in multi-unit NPPs and investigate the system's ability to resist risks [7].

For this paper, based on the group reliability model proposed by Furuta et al. [8], a modified model for the analysis of group reliability in multi-unit NPPs following the key characteristics of inter-unit sharing and collaborations has been proposed at first. Then, in order to further investigate the resilience of group under emergency, the impact of incident on the parameters of that model has been identified, and the simulations of the group reliability model under some typical incident scenarios have been carried out. With the group response of reliability under the change of parameters, the metrics for the measurement of resilience have been proposed. Preliminary study has shown that in terms of the unit suffering more severe damage, inter-unit collaboration can effectively make the group more resistive to an emergency and enhance the recovery rapidity, timely resource sharing between units can effectively offset the degradation of group reliability and improve the site-level resilience of group reliability.

2. RELATED WORK

2.1. Mathematic model of group reliability

Furuta et al. have developed a method of evaluating human reliability of group by modeling a group as a Markovian network, and performed analysis in the control room setting of single-unit NPP [8-9]. In their model, the nodes represent group members and they are connected with each other. Each member is assumed to be a simple information processor which may take two kinds of state: +1 represents the state of making a correct decision and -1 that of a wrong decision. A group of size N has 2^N distinct configurations of states, and every configuration may change to another if any one of the member changes his/her state.

This model assumes that the processing of making a decision is influenced by the ability level of each member (β_i), the influence from the other members (ω_{ij}), and the information available from the environment ($\omega_i\sigma_i$). Assume that the average speed of making decision for the i_{th} member is λ_i, and the state of the i_{th} member in the k_{th} configuration is S_i^k, the transition probability matrix from the k_{th} to the l_{th} configuration, which is different in the state of just one member, is given as

$$G_{kl} = \frac{\lambda_i}{1 + \exp[S_i^k(\phi_i^k + \beta_i)]} \tag{1}$$

where ϕ_i^k represents the total worth of the information obtained by the i_{th} member in the k_{th} configuration, which is determined by the other members ($\sum\omega_{ij}S_j^k$) and the environment ($\omega_i\sigma_i$) as

$$\phi_i^k = \sum_{j \neq i} \omega_{ij} S_j^k + \omega_i \sigma_i \tag{2}$$

By numerically solving the differential equation of this Markov process, the probability distribution π_l at the moment t can be obtained, and the probability of group success, i.e. group reliability, can be evaluated by

$$P(t) = \sum_l T_l(t)\pi_l(t) \tag{3}$$

where T_l is the conditional probability of group success for the l_{th} configuration. In the control room setting of NPP, the group leader plays the role of making decisions for the group. Under the social decision scheme by Davis [10], the state of the leader represents directly the success/failure state of the group.

2.2. Measurement of resilience

The concept of resilience has been originally originated from the engineering mechanics. It has been used to describe the ability of materials to absorb deformation forces during plastic deformation or fracture processes, and then gradually applied to such diverse fields as ecology, psychology, engineering, social and economics. The common use of resilience implies the ability of an entity or system to return to normal condition after the occurrence of an event that disrupts its state [5]. So far, several measurement of resilience have been offered [11]. Among them, Bruneau et al. have proposed a framework to quantitatively assess the resilience based on the measurement of system functionality in an emergency [12]. In their framework, resilience can be understood as the ability of the system to absorb the damage (i.e. abrupt reduction of functionality) and to recover quickly after the emergency (re-establish normal functionality). Therefore, when emergency occurs, the index that characterize the system functionality $Q(t)$ suddenly reduces at first, and then gradually recovers through the absorption and adaptability of the system itself. This dynamic adjustment process can be described by the ‘resilience triangle’.

In the 'resilient triangle', one edge of the right triangle shows the decrease of system functionality (Q_0- Q_a) at time t_0, while the other edge shows the time that required for system recovery (t_r-t_0). Thus, the resilience metric derived from "resilience triangle' generally capture two features of resilience: the functionality loss and the speed or duration for functionality recovery. Related measurements are given as

$$Resilience\ Loss = \int_{t_0}^{t_r} [Q_0 - Q(t)]\mathrm{d}t \tag{4}$$

$$Rapidity = (Q_0 - Q_a)/(t_r - t_0) \tag{5}$$

However, no single indicator can fully describe the multifaceted property of resilience. Reed et al. then proposed an index of resilience, which can comprehensively represent the feature of resilience with one parameter at any time t_h. This index has been widely used for resilience analyses of various infrastructure systems [13].

$$R(t_h) = \int_{t_0}^{t_h} Q(t)dt \Big/ t_h - t_0 \tag{6}$$

3. METHOD

3.1. Model of multi-unit group reliability

The group reliability model [8] was modified to fit the setting of multi-unit NPP according to the human and organizational characteristics relevant to multi-unit incident scenario. Correlational researches [14-15] in this filed have already identified the critical characteristics that can be distinguished in organizational behavior between single- and multi-unit, as summarized in Table 1.

Table 1. Comparison of organizational behavior characteristics between single- and multi-unit

Characteristics		**Single-unit**	**Multi-unit**
Organiza-tional factors	Personnel	MCR operators of single unit and the operators of equipment related to the safe operation of this single unit.	MCR operators of each unit, operators of equipment related to safe operation of each unit, and personnel responsible for coordination and overall scheduling, such as technical support center, business support center, emergency management center, etc.
	Work devices	Equipment related to the safe operation of single unit.	Equipment related to the safe operation of each unit, including fixed equipment, shared equipment, mobile equipment, etc.
Condition of group success		Successfully completing tasks related to the safe operation of single unit to ensure its safety.	Successfully completing tasks related to the safe operation of each unit under the impact of equipment sharing/task overlap between units to ensure the safety of all the units.

Therefore, the node attributes and the conditional probability were modified to fit the setting of multi-unit NPP. In terms of node attributes, two special types of member have been distinguished in a multi-unit model: one was the personnel responsible for performing safety operations in each unit, and the other was the personnel responsible for communication and coordination between units. Therefore, three types of node attributes were set in the model of multi-unit group reliability, as shown in Table 2.

Table 2. Node classification in the multi-unit group reliability model

Category	**Explanation**
Type 1	The personnel responsible for performing safety operations in each unit
Type 2	The personnel responsible for communication and coordination between units
Type 3	The personnel responsible for cooperating with other two types of personnel to ensure the safe operation of each unit of the site

Taking a NPP with two units as an example, each unit is assumed to equip with 4 staff members, as shown in Figure 1. The red nodes represent the first type personnel (nodes 1 and 5), the blue nodes represent the second type (nodes 4 and 6), and the white nodes represent the third one (nodes 2, 3, 7, 8). The connections among nodes indicate the communication of information between members. In each unit, four staff members communicate with each other. The information exchange and resource coordination between units is achieved through the communication between the second type personnel in blue.

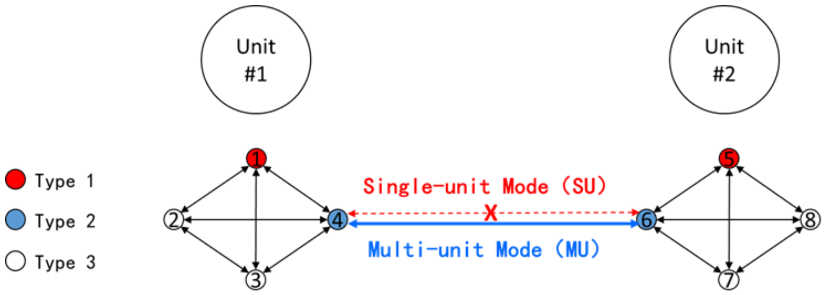


Figure 1. Example of group reliability model in a NPP with two units

The conditional probability of the group reliability model in multi-unit NPP was modified as: if and only if the member responsible for the critical safety operations (Type 1) of both units make the correct decisions. As shown in Figure 1, the conditional probability is defined as

$$T_l = \begin{cases} 1(\text{if } S_1^l = S_5^l = 1) \\ 0(else) \end{cases} \tag{7}$$

Based on the relatively simplified assumptions mentioned above, we have studied the impact of inter-unit cooperation on the group reliability of multi-unit NPP in our previous study, and have proven that the inter-unit collaboration can effectively improve group reliability in situations of insufficient resources [16].

3.2. Measurement of resilience for group reliability

In the framework of the above model, the group reliability is actually influenced by the members' individual ability, the interaction between members, and the environment. For a group that has undergone the normal and stable situations for a long time to reach an equilibrium state, when suddenly entering a state of emergency, transient behavior will occur due to the disturbance on the parameters of group reliability model. In this study, it was assumed that a state of emergency might affect the members' interactions and the environmental factors. However, the member's individual ability and attitude (information seeking tendency) were long-term personal quality and should remain unchanged during the emergency. The parameters in the above model and their changes under emergency are shown in Table 3.

Table 3. Changes of parameters in an emergency

Parameter	Meaning	Changes under emergency
ω_i	Information seeking tendency of the i_{th} member	Remain unchanged
ω_{ij}	Influence strength from the j_{th} to the i_{th} member	Communication channel might be cut off
σ_i	Worth of the information available from the environment of the i_{th} member	Damage might limit the information available from the environment
β_i	Personal ability level of the i_{th} member	Remain unchanged
λ_i	Average speed of making decisions of the i_{th} member	Rapid increase in tasks might lead to rapid increase of decision-making speed

Now we focus our attention on the time dependent behavior of a group under various parameter disturbances and propose the measurement of resilience.

σ_i and λ_i At the beginning of an emergency, a rapid increase in the tasks imposed on group members would lead to a low probability of group success, which can be modeled through the change of average decision speed of each group member (λ_i) and the worth of the information available from the environment (σ_i) in this model. Since there is a proportional relationship between the total number of tasks and the average decision speed (λ_i), a state of emergency can be modeled through the method that the decision speed (λ_i) is increased suddenly at the beginning of the emergency and then returned exponentially to the normal level. Considering that the resources are limited due to the damage of the incident, the information available from the environment (σ_i) could be decreased suddenly at the beginning of the emergency and then returned exponentially to the normal level. The disturbance of parameters in emergency are shown in Figure 2.

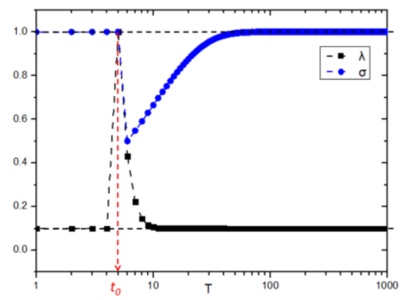


Figure 2. Disturbance of parameters of an emergency

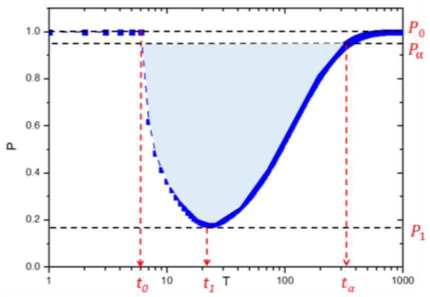


Figure 3. Group response to an emergency

Assuming that the expected decision interval at the beginning of the emergency is the unit of time, the state transition matrix after the occurrence of an emergency can be given as

$$G_{kl} = \frac{\lambda_i}{1+\exp[S_i^k(\phi_i^k + \beta_i - \upsilon\lambda_i)]} \tag{8}$$

where the parameter υ is the coefficient for the decision speed (λ_i) under emergency. Figure 3 presents the group response to such emergency when the parameter υ was set to be an arbitrary value of 0.1. This group have undergone a stable situation and reached an equilibrium state with group reliability P_0. At time t_0, an emergency occurred, and the group reliability gradually reduced to P_1 until time t_1, then slowly recovered to P_α until time t_α. It is worth noting that the group reliability cannot recover to the pre-incident level (P_0). In order to measure the rapidity of recovery, t_α was defined as the time when the group reliability recovered to α% of its pre-incident level, i.e. $P_\alpha/P_0=\alpha\%$. Two metrics that characterize the feature of resilience in an emergency were introduced as follows: the degradation in group reliability (from P_0 to P_1) and the time to recovery (from t_1 to t_α). In order to eliminate the effect of the order of magnitude, they were normalized respectively and defined as

$$Loss = {(P_0 - P_1)}/{P_0} \tag{9}$$

$$Rapidity(\alpha\%) = {(t_\alpha - t_1)}/{(t_\alpha - t_0)} \tag{10}$$

Under the definition, larger values of *Loss* represented lager degradation in group reliability at the beginning of the emergency, and larger values of *Rapidity* represented slower recovery after the occurrence of emergency. They both indicated less resilient systems. In order to comprehensively represent the feature of resilience with one parameter, the *Resilience* of group reliability was defined as

$$Resilience\,(\alpha\%) = 1 - Loss \times Rapidity(\alpha\%) \tag{11}$$

w_{ij} During emergency, some members might be cut off from the group and become isolated until assistance arrived. In this model, such change can be considered as the complete interruption of communication between the affected member and others. However, our previous study has already proved that the Type 2 personnel, who were responsible for communication and coordination between units, had the most prominent effect on group reliability of multi-unit NPP, because the insufficient ability of Type 2 personnel would mislead the group decision-making for all and result in a low probability of group success in multi-unit NPP [16]. Therefore, we proposed Single-Unit and Multi-Unit modes for comparative analysis. As shown in Figure 1, in the single unit mode (denoted as SU), two units operated independently, and there was no information exchange or resource collaboration between node 4 and node 6. In the multi-unit mode (denoted as MU), two units exchanged their information and resources through communication between node 4 and node 6.

4. SIMULATION

4.1. Parameter and scenario design

Our previous study has already found the parameter combination ensuring the convergence of the proposed model through numerical simulation analysis [16]. This study continues to adopt such parameter combination, with a focus on the time dependent behavior of the multi-unit group reliability in an emergency. The unchanged parameters were designed as shown in Table 4:

Table 4. Parameter design in the model of multi-unit group reliability

Parameter	Meaning	Value
ω_i	Information seeking tendency of the i_{th} member	10
ω_{ij}	Influence strength from the j_{th} to the i_{th} member	2
β_i	[ersonal ability level of the i_{th} member	-8

The parameter υ in function (8) is assumed to be an arbitrary value of 0.1. The resilience of group reliability of double-unit model in an emergency was compared among three typical incident scenarios. At Scenario #1, emergency occurred on one of the units and the other unit was not affect. The changes of λ and σ after the occurrence of the emergency of Unit #1 and Unit #2 were shown in Figure 4(a). At Scenario #2, emergency occurred simultaneously on both units and the changes of parameters in the emergency were shown in Figure 4(b). At Scenario #3, emergency affected two units successively and the disturbances of parameters were shown in Figure 4(c).

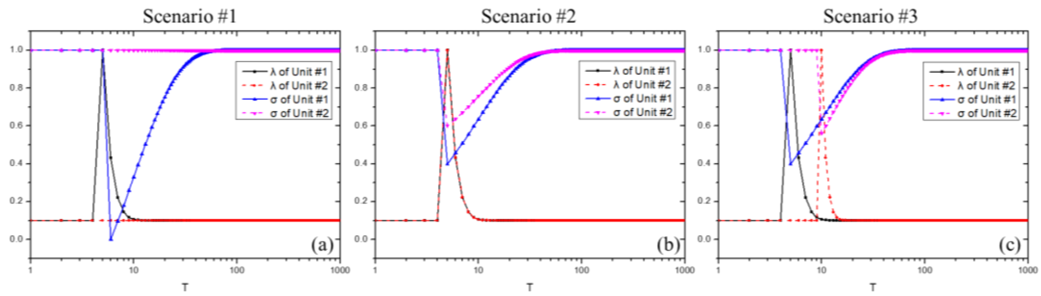


Figure 4. The changes of λ and σ at typical incident scenario cases

4.2. Impact of inter-unit collaboration

The impact of inter-unit collaboration on the change of group reliability among three incident scenarios was analyzed through comparing the group resilience between SU and MU mode. The results of Scenario #1 were shown in Figure 5. At the SU mode, the group reliability of Unit #1 showed a great decrease due to the increase in tasks and decrease in resources. While at the MU mode, the united group reliability of MU mode showed a less decrease and a faster recovery than that of SU mode. Set α to be 0.95, the *Resilience* of group reliability at SU/MU can be measured by function (9)-(11) and the results were shown in Table 5.

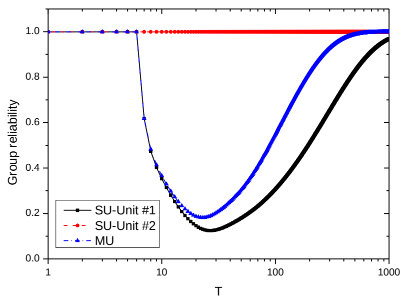


Figure 5. Comparison of change of group reliability between SU and MU at Scenario #1

Table 5. Resilience index of group reliability at Scenario #1 (SU and MU mode)

Mode	*Loss*	*Rapidity*	*Resilience*
SU-Unit #1	0.8753	0.9753	0.1463
SU-Unit #2	0	0	1
MU	0.8179	0.9491	0.2237

Judging from the results obtained, in terms of Unit #1, there existed less degradation of group reliability and faster recovery after the emergency at MU mode. At Scenario #1, inter-unit collaboration can effectively make the group more resistive to an emergency and enhance the system reliability.

The results of Scenario #2 were shown in Figure 6 and Table 6. Assuming that the Unit #1 suffered more severe damage, inter-unit collaboration can help to offset the degradation of reliability in terms of Unit 1# at SU mode, and effectively enhance the recovery speed of both Unit #1 and Unit #2.

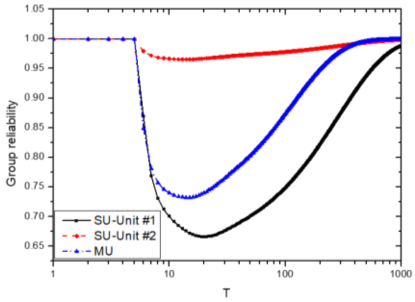


Figure 6. Comparison of change of group reliability between SU and MU at Scenario #2

Table 6. Resilience index of group reliability at Scenario #2 (SU and MU mode)

Mode	*Loss*	*Rapidity*	*Resilience*
SU-Unit #1	0.3338	0.9829	0.6719
SU-Unit #2	0.0339	0.9904	0.9665
MU	0.2672	0.9737	0.7398

The results of Scenario #3 were shown in Figure 7 and Table 7. Assuming that the Unit #1 suffered more severe damage earlier, inter-unit collaboration can also help to offset the loss of reliability in terms of Unit 1# at SU mode, and effectively enhance the rapidity of both Unit #1 and Unit #2.

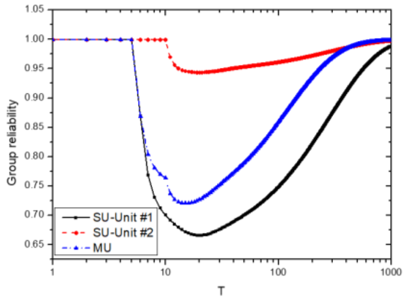


Figure 7. Comparison of change of group reliability between SU and MU at Scenario #3

Table 7. Resilience index of group reliability at Scenario #3 (SU and MU mode)

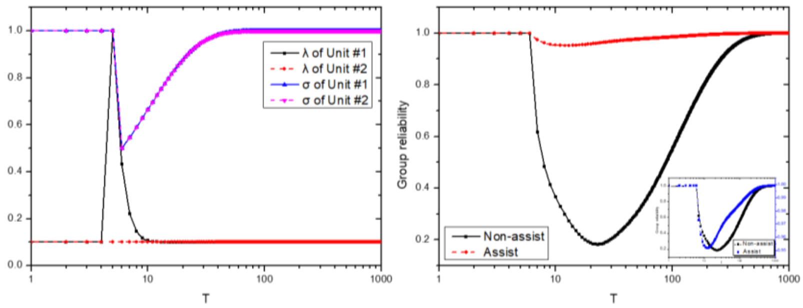
Mode	*Loss*	*Rapidity*	*Resilience*
SU-Unit #1	0.3338	0.9829	0.6719
SU-Unit #2	0.0557	0.9824	0.9452
MU	0.2787	0.9753	0.7282

It can be inferred from the above two cases that, for emergency affecting on both units, if it was required to handle emergency as soon as possible, the mode of MU (inter-unit collaboration) should be adopted; If it was required to reduce the impact on the other unit, the mode of SU (independent operation) was recommended.

In the above three cases, units that were not affected or less affected always hold the higher *Resilience*. In order to enhance the resilience of all the unit at site level, the most effective method seems to be the inter-unit assistance. For simplicity, the limited resources were shared and allocated from the higher *Resilience* unit to the lower one. The impact of inter-unit assistance on the change of group reliability among three scenarios was simulated as below.

4.3. Impact of inter-unit assistance

In order to compare the impact of inter-unit assistance, at Scenario #1, it was assumed that Unit #1 suffered the damage and the Unit #2 assisted and shared its resources (i.e. the information available from the environment—σ) at the very beginning of the emergency, as shown in Figure 8(a). The results were shown in Figure 8(b) and Table 8. It is obvious that inter-unit assistance can effectively reduce the loss of group reliability and enhance the resilience.



(a) (b)

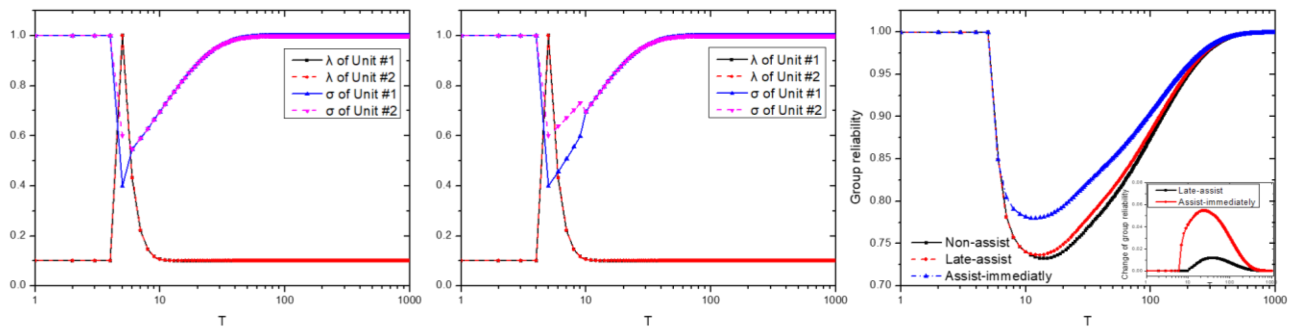
Figure 8. Parameter design and the comparison of assistance at Scenario #1

Table 8. Resilience index of group reliability at Scenario #1 (comparison of assistance)

Case	*Loss*	*Rapidity*	*Resilience*
Non-Assist	0.8179	0.9491	0.2237
Assist	0.0475	0.9760	0.9536

However, it is impossible to start rescue at the very beginning of an incident. In order to further investigate the time-dependent impact of inter-unit assistance, at Scenario #2, two different assist cases were considered, as shown in Figure 9. For assist mode 1(Figure 9(a)), the Unit #2 assisted and shared its resources after only one unit time of the emergency, which represented 'assist immediately' case. For assist mode 2 (Figure 9 (b)), the Unit #2 assisted after several unit of time, which represented 'late assist' case.

The results of Scenario #2 were shown in Figure 9(c) and Table 9. It is obvious that since the recovery speed of the three cases are similar, the main factor affecting the result of rescue is the value of group reliability at the beginning of the assistance. For the case of 'late assist', the group reliability has already been close to the P_1 of 'non assist' at the beginning of assistance, the enhancement in resilience is not significant enough. However, the case of 'assist immediately' can effectively reduce the loss of reliability, and increase the resilience of system.



(a) (b) (c)

Figure 9. Parameter design and the comparison of assistance at Scenario #2

Table 9. Resilience index of group reliability at Scenario #2 (comparison of assistance)

Case	*Loss*	*Rapidity*	*Resilience*
Non-Assist	0.2672	0.9737	0.7398
Late-Assist	0.2632	0.9763	0.7431
Assist-immediately	0.2194	0.9793	0.7852

At Scenario #3, two cases of ‘assist immediately’ and ‘late assist’ were also considered, as shown in Figure 10(a) and (b). The results of Scenario #3 were shown in Figure 10(c) and Table 10. It is clear that in case of ‘late assist’, the rescue started too late so that the group reliability has already reached its minimum, and such assistance was almost ineffective. But the timely inter-unit assistance can help to offset the loss of reliability, and effectively enhance the resilience. Especially under the premise of ensuring that the resources of the other unit are not affected, starting assist immediately at the beginning of one single unit accident would result in a better resilience for site-level group reliability.

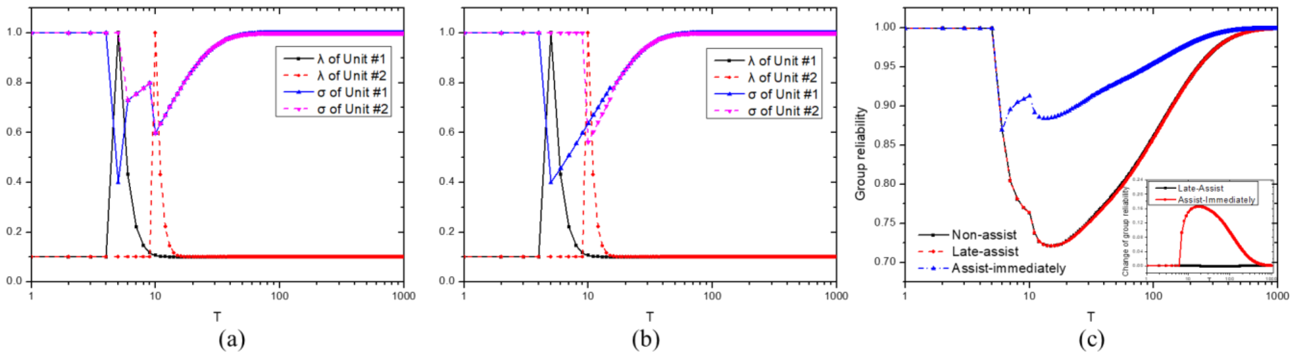


Figure 10. Parameter design and the comparison of assistance at Scenario #3

Table 10. Resilience index of group reliability at Scenario #3 (comparison of assistance)

Case	*Loss*	*Rapidity*	*Resilience*
Non-Assist	0.2787	0.9753	0.7282
Late-Assist	0.2787	0.9753	0.7282
Assist-immediately	0.1304	0.9969	0.8700

5. CONCLUSION

This study proposed a simplified model to evaluate the group reliability considering the inter-unit interactions for multi-unit NPPs, and then presented a framework to measure the resilience of group reliability in multi-unit NPPs. Under the relatively simplified model assumptions and simulation scenario design, this study found that:

(i) Inter-unit collaboration can effectively make it more resistive to an emergency in terms of the unit suffering more severe damage and enhance the recovery rapidity of both units.

(ii) Timely inter-unit assistance can help to offset the loss of reliability, and effectively enhance the resilience of reliability.

Based on the findings, it can be inferred that for emergency situations that affect multi units, inter-unit collaboration (i.e. MU mode) is suggested for the requirement of rapid recovery, while the mode of independent operation (i.e. SU mode) is recommended for the purpose of minimizing the impact on the other unit. Starting assist immediately at the beginning of one single unit accident, while ensuring that the resources of other units are not affected by the accident, will result in a better resilience for site-level group reliability.

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