Development of Multi-Unit Dependency Evaluation Model Using Markov Process and Monte Carlo Method

Sunghyon Jang, and Akira Yamaguchi
Department of Nuclear Engineering and Management, The University of Tokyo, Tokyo, Japan

Abstract: T A risk assessment of multi-unit by a typical event tree (ET) method is insufficient because the state of the plant will vary by a plant status of the adjacent unit. In this study, a new approach of scenario quantification method of multi-unit Nuclear Power Plants (NPPs) using Markov process and Monte Carlo method is proposed to evaluate interactive time-transient accident scenario progression which considered the effect of an adjacent unit. The impact (positive and negative effect) of the adjacent unit (multi-unit) on a single unit is modeled to change failure probability of each heading in the ET. Markov process is adopted to estimate transient plant status using a fault tree (FT) analysis. Markov process decides the plant status at the present time step only based on the status of the previous time step. Also, Monte Carlo method is used to decide the current plant status by comparing a random variable with the transient plant state. Rather than giving branch probabilities in the ET, the current failure probabilities of each heading of the ET are used to decide accident progression. By using this methodology, the influence of multi-unit and dynamic and interactive accident scenario progression can be evaluated.

This methodology was applied for accident scenario quantification of two unit systems with consideration of the multi-unit dependencies caused by the initiating event, identical component, proximity, and shared connection. The result showed that an effect of a power sharing (shared connection) decreased number of accident scenario of core damage in single and two units.

Keywords: Multi-Unit Dependency, Dynamic PRA, Markov Process, Monte Carlo Method

1. INTRODUCTION

Most nuclear generation sites worldwide have more than one reactor in operation [1-2]. In some sites, NPPs are physically located near to each other such that they are essentially challenged by the same external hazards. There are some benefits of installation of multi-unit NPPs at a single site.
(1) Reducing costs by sharing mechanical and electrical support systems and resources between NPPS is available. (2) Fulfilling site selection criteria for new NPP installation takes time and effort. On the other hands, some disadvantages such as inter-unit interaction, common case failure, and lack of resource and personnel under a severe accident condition, are existed in multi-unit NPPs [3].

Currently, most Probabilistic Risk Assessments (PRA) of NPPs have focused on estimating the risk of a single NPP, which may or may not be co-located with other NPPS. However, a plant status of a single unit can be influenced by a status of adjacent units in multi-unit site.

For example, in Fukushima Daiichi accident, a hydrogen explosion took place at Unit 1 and 3 and it brought damages on electric cables, fire cars and power cars in unit 2, as a result of the hydrogen explosion, recovery actions were disrupted. Also, the loss of electrical power (AC and DC) accelerated accident progression and made it more severe.

These multi-unit dependencies should be modeled to evaluate intrinsic accident scenario in a multi-unit site. However, there are still no well-established, comprehensive methods for modeling multi-unit site dependencies in a PRA.

Thus, in this study, a new approach of scenario quantification method of multi-unit NPPs using Markov process and Monte Carlo method is proposed to evaluate interactive time-transient accident scenario progression which considered the effect of an adjacent unit. The impact (positive and negative effect) of the adjacent unit (multi-unit) on a single unit is modeled to vary a state transition probability of one unit. Monte Carlo method is used to decide the current plant status by comparing a random variable with the transient plant state. By using this methodology, the influence of multi-unit and dynamic and interactive accident scenario progression can be evaluated.

2. ANALYSIS OF INTER-UNIT DEPENDENCY IN MULTI-UNIT SITE

2.1. Classification of Inter-unit dependency in Multi-unit Site

There are some approaches to classify multi-unit dependencies. For example, Schroer classified multi-unit dependencies into 6 categories based on past multi-unit events reported in NRC Licensee Event Reports [4]. Initiating event, shared connection, identical components, proximity dependencies, human dependencies and organizational dependencies are the 6 categories for multi-unit dependency. Analytical model to evaluate each multi-unit dependencies were suggested, however, it is a challenge and complicated to evaluate several different multi-unit dependencies at the same time, since different methodologies are required to evaluate these multi-unit dependencies. Thus, we propose an analytical model to evaluate influence of initiating event, shared connection, and proximity dependency by using a state transition probability based on Markov process [5].
In this study, we consider multi-unit dependencies caused by an initiating event, proximity, identical component and shared component, which exert influence on accident progression.

2.2. Accident Progression with Multi-unit Dependencies

As shown in Figure 1, in multi-unit site, it is expected that multi-unit dependencies have influence on accident even progression at following timing.

1)When an initiating event takes place
Components installed in each reactor system get damage and lost its function by an initiating event due to a proximity of components, vulnerability comes its identity.

2) While safety functions are in operation
The initial status of the plant system will be decided by the occurrence of an initiating event, remaining system components start to work to maintain safety function in the reactor system. Multi-unit dependencies such as shared connections, identical components, and proximity dependencies may be revealed.

3) While recovery actions are tried
When certain components are failed, recovery actions are attempted. However, a lack of resources such as water, power and personnel, and the proximity dependency may delay the recovery action.

In this study, we expect that multi-unit dependencies are revealed on such occasions and have an influence on the reactor system by making a component be failed more and be recovered more difficult or vice versa. In order to model the influence of multi-unit dependencies on the reactor system, a transition state model using Markov process are used.

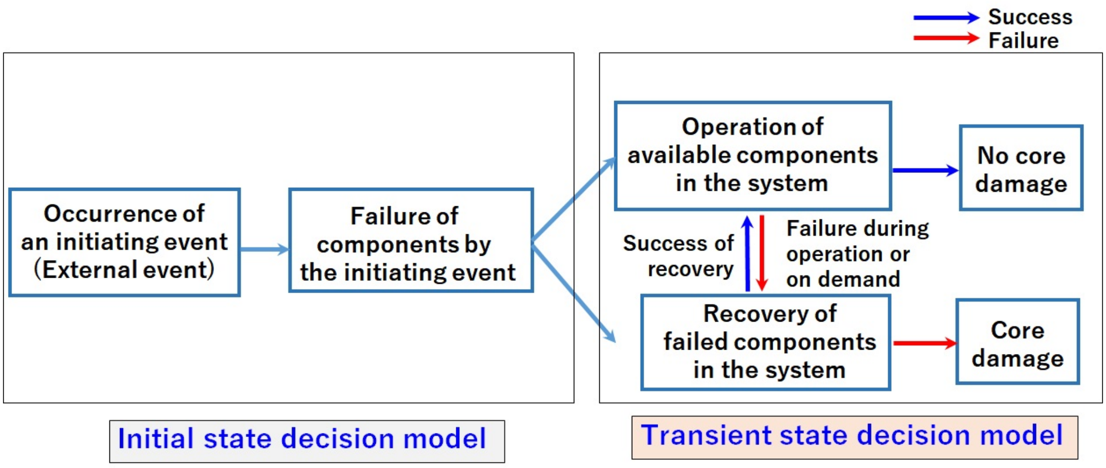


Figure 1 Concept of accident progression with multi-unit dependency

3. MULTI-UNIT DEPENDENCY EVALUATION MODEL

3.1. State Transition Probability Based on Markov Process

In this study, we focus on evaluation of a system which have several components. As shown in Figure 2, a state transition model is used to evaluate the state of components at each time step for two component which are independent each other (Fig.2-a) and has dependency between components.

In this figure, the two components are represented as A, and B. Each component has two state condition, which is being intact and failed. If two components are independent each other, the state transition of each component can be evaluated simply. However, when two system has a dependency, in other words, the state of one system can be affective by the state of the other system, the state transition model can be described as shown in Fig2-b. The state of both components are in intact condition, it can be expressed as (A_I, B_I) in Figure 1. Arrows in the figure represent a direction of the state transition. If the component A become in a failed condition, while the other component, B is still intact, it can be figured out as (A_F,B_I) A state of each component can be evaluated by using Markov process. Markov process refers to a transition state process in which the state of the system at the next time depends only on the current system state.

When the component A and B are intact state and has a failure probability of $\lambda(A_I B_I, A_F B_I, t)$ and, $\lambda(A_I B_I, A_I B_F, t)$ respectively, it is expected that the state of (A_I, B_I) has a possibility to transit to the state (A_F,B_I) with a probability of $\lambda(A_I B_I, A_F B_I, t)$ and also have a possibility to transit to the state (A_I,B_F) with a probability of $\lambda(A_I B_I, A_I B_F, t)$, respectively. At the same time, there are possibilities that the state (A_F,B_I) and (A_I,B_F) to transit to the state (A_I, B_I), which is a recovery; with a probability of $\mu(A_F B_I, A_I B_I, t)$ and $\mu(A_I B_F, A_I B_I, t)$ respectively. Likewise, a probability that the plant will be in the state of (A_F,B_I), can be obtained by solving a partial different equation using a failure rate (λ), and a recovery rate (μ) as shown below.

$$\begin{aligned}\frac{dP(\boldsymbol{A_I B_I, t})}{dt} = &-P(\boldsymbol{A_I B_I, t}) \cdot \boldsymbol{\lambda}(\boldsymbol{A_I B_I, A_I B_F, t}) - P(\boldsymbol{A_I B_I, t}) \cdot \boldsymbol{\lambda}(\boldsymbol{A_I B_I, A_F B_I, t}) \\ &-P(\boldsymbol{A_I B_I, t}) \cdot \boldsymbol{\lambda}(\boldsymbol{A_I B_I, A_F B_F, t}) + P(\boldsymbol{A_F B_I, t}) \cdot \mu(\boldsymbol{A_F B_I, A_I B_I, t}) \\ &+P(\boldsymbol{A_I B_F, t}) \cdot \mu(\boldsymbol{A_I B_F, A_I B_I, t}) + P(\boldsymbol{A_F B_F, t}) \cdot \mu(\boldsymbol{A_F B_F, A_I B_I, t})\end{aligned} \quad (1)$$

Where,

P $(A_i B_j, t)$: probability that unit *A* and *B* are in state i and j, respectively at time t

$\lambda(A_i B_j, A_{i'} B_{j'}, t)$: failure probability that a state of unit *A,B* transits from one state at time t to another state in next time step

$\mu(A_i B_j, A_{i'} B_{j'}, t)$: repair probability that a state of unit *A,B* transits from one state at time t to another state in next time step

suffix *i,j*: states of unit *A,B* before transition occurs, *i',j*: states of unit *A,B* after transition occurs . *i* and *j* either I or F which represents intact, F represents being failed, respectively

Likewise, probabilities that the system would be in each state could be expressed by considering state transition in Figure 2.

In order to evaluate complex multi-unit dependency in real reactor system at a multi-unit site, state transition probabilities, which are failure rate and recovery rate, could be determined by using a fault tree methodology or causal Bayesian network analysis coupled with thermal hydraulic analysis (severe accident analysis).

In this study, a simple system consist of several components was used to evaluate feasibility of the multi-unit dependency evaluation model.

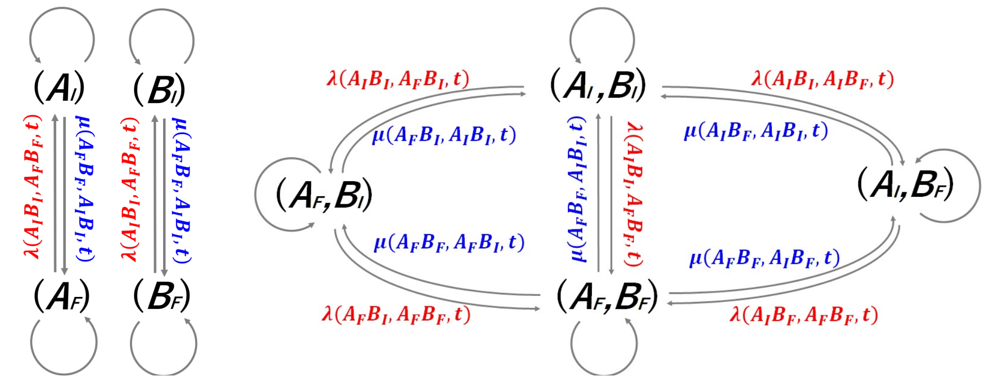
Two different failure mode, failure during operation, failure on demand, were considered. The probability of loss of function for equipment per unit time is expressed by the following equation.

$$\frac{\partial p}{\partial t} = (1 - p)\lambda \quad (2)$$

Where, p: probability of loss of function status [-], λ : failure rate [1/min], t: time [min].

By integrating the failure rate as a constant, the cumulative distribution function is obtained. This represents the probability that the function has already been lost at time t.

$$p(t) = 1 - e^{-\lambda t} \quad (3)$$



(a) (b)

Figure 2. State transition model for two components (a) without multi-unit dependency, (b) with multi-unit dependency

Table 1: Transition state probabilities

Transition probability	(A_I,B_F)			
Initial state	(A_I,B_I)	(A_F,B_I)		(A_F,B_F)
(A_I,B_I)		$\lambda(A_IB_I, A_FB_I, t)$	$\lambda(A_IB_I, A_IB_F, t)$	$\lambda(A_IB_I, A_FB_F, t)$
(A_F,B_I)	$\mu(A_FB_I, A_IB_I, t)$			$\lambda(A_FB_I, A_FB_F, t)$
(A_I,B_F)	$\mu(A_IB_F, A_IB_I, t)$			$\lambda(A_IB_F, A_FB_F, t)$
(A_F,B_F)	$\mu(A_FB_F, A_IB_I, t)$	$\mu(A_FB_F, A_FB_I, t)$	$\mu(A_FB_F, A_IB_F, t)$	

The state transition model can evaluate the probability that a certain state of a component to proceed to other states at next time step. A decision that in which state the current state is necessary and the decision can be made by comparing the transition state probability with a random number generated by Monte Carlo method. The details are explained in the following section.

3.2. Concept for evaluation of multi-dependencies for common cause failure

A common cause failure caused by identical component and proximity is important issue to be solved to evaluate multi-unit dependency. In this study, it is assumed that the failure rate (transition probability) of each component in the system, can be divided into an inherent part and a common part. Let us assume that transition probability (failure rate) that system A and system B lost its function as $\lambda(A)$, and $\lambda(B)$.

$$\lambda(A) = \lambda(A_i) + \lambda(C) \quad (4)$$
$$\lambda(B) = \lambda(B_i) + \lambda(C) \quad (5)$$

where, $\lambda(A_i)$ and $\lambda(B_i)$ are inherent part of the failure rates of component A and B respectively, $\lambda(C)$ is the part of failure rate of component A and B caused by common cause.

Here, we assume that $\lambda(A_i)$, $\lambda(B_i)$, and $\lambda(C)$ follow standard distribution and have averages of μ_{A_i}, μ_{B_i}, and μ_C and standard deviations of σ_{A_i}, σ_{B_i}, and σ_C.

Thus, the failure rates of the system A and B, which are $\lambda(A)$, and $\lambda(B)$ can be written to have correlation which represents common cause failure as follow.

$$\lambda(A) \sim N\left(\mu_{A_i} + \mu_C, {\sigma_{A_i}}^2 + {\sigma_C}^2\right) \quad (6)$$
$$\lambda(B) \sim N\left(\mu_{B_i} + \mu_C, {\sigma_{B_i}}^2 + {\sigma_C}^2\right) \quad (7)$$

Since $\lambda(A)$ and $\lambda(B)$ are probability, it has a value between 0 to 1. Thus, the standard deviation of the probabilities are decided to be that 99.7% of a random sampling number for probabilities are existed in a range of 3σ from the average μ as the equation 8.

$$\sigma_{A_i} = \frac{\mu_{A_i}}{3}, \sigma_{B_i} = \frac{\mu_{B_i}}{3}, \sigma_C = \frac{\mu_C}{3} \quad (8)$$

3.3. Continuous Markov process and Monte Carlo method

The conventional event tree method has a deterministic aspect which requires pre-specification of event order occurrence which may vary significantly and the probability of events occurrence such as failure probability of equipment, human error. A predetermined order of occurrence of events in ET is required to evaluate accident sequences. However, in a multi-unit site, it is expected that the predetermined event order might be changed by events occur at surrounding units.

Thus, we adopt a dynamic scenario quantification method which is based on Continuous Markov process and Monte Carlo (CMMC) method. The CMMC method is a combining method of Markov chain and Monte Carlo. The CMMC method has been applied for scenario quantification for dynamic PRAs [5].

Transition probabilities of a component (system) which is in a certain state and proceeds to other states at the next time step can be evaluated by the state transition model based on Markov process.

The state transition model was used to evaluate accident sequences in multi-unit site in the former section. At every time step, the transition state model can evaluate status of components or system by calculating state transition probability that a certain state to proceed to other states at the next time step. For example, if a plant is in an intact state and has a failure rate is larger than a random number generated by Monte Carlo method, it is regarded that a state of the system for the next state is failed. On the other hand, if a failure rate is smaller than a random number it is regarded that the system keeps its intact state at the next time step. Here, a decision that in which state the current state is necessary and this decision can be made by comparing the transition state probability with a random number generated by Monte Carlo method.

By deciding the plant status at each time step by comparing transition probabilities by failure and recovery and a random number generated by Monte Carlo method, it is possible to evaluate time transient system state.

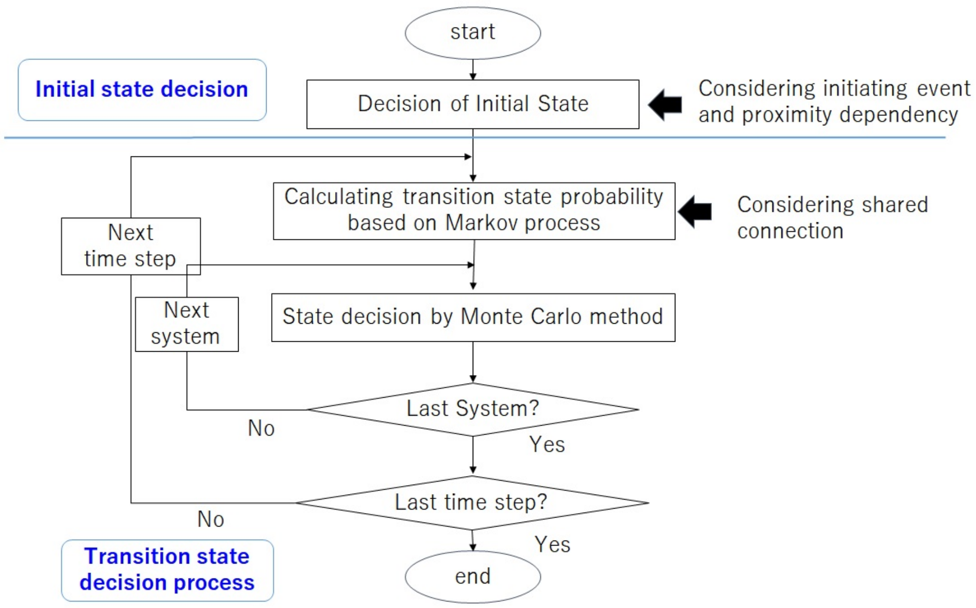


Figure 3 Algorithm of continuous Markov process and Monte Carlo method.

Figure 3 shows algorithm flow for Continuous Markov process and Monte Carlo method for accident sequence quantification for multi-unit site. At first, the initial state is decided by considering an influence of initiating event and proximity dependency. As a consideration of initiating event and proximity dependency, available and unavailable components are decided. Next, state transition probabilities of components are decided based on Markov process model by considering physical properties. Then, decision that whether the state of the component is changed at the next time step by comparing the state transition probabilities and a random number generated by Monte Carlo process. Multi-unit dependencies are considered in evaluating state transition probabilities. By repeating these process for the whole component in the system until the end of the analytical time, unique accident sequences, which are revealed by a combination of states of all components at each time step.

4. ACCIDENT SCENARIO QUANTIFICATION FOR TWO-UNIT SYSTEM

4.1. Description of accident scenario

1) Initiating event

A seismic-induced loss of offsite power (LOOP) is considered as an initiating event. 750 gal is a postulated ground motion for the initiating event. It is expected that when an earthquake occurs, the reactor scram is successfully done. However, some component gets damaged and stop to operate due to the initial event, and proximity dependency is considered when components, which are located in the same building, lost its function due to damage in the building.

2) Reactor system

Two BWR reactor systems are considered target system in this study. Each system has functions of reactor scram, and depressurization, and water injection. These functions are expected to operate in a severe accident condition. Each function consists of several components. For example, the water injection system is composed of the high pressure injection system, and the low pressure injection system. The high pressure injection system has the high pressure coolant injection (HPCI), reactor core isolation cooling (RCIC) and etc., the latter has the low pressure coolant injection (LPCI), low pressure core spray (LPCS), fire protection system, and etc.

In this study, for simplicity, it is assumed that each system has a single system, which is the safety relief valve (SRV) for the depressurization, and the high pressure coolant injection (HPCI) system, the fire protection (FP) system, for the high pressure and low pressure injection system, respectively, and the emergency diesel generator for the AC power supply.

Figure 4 shows the target system which has two reactor buildings but shares turbine building. Arrangement of components are decided by referring a cross-sectional diagram of reactor buildings in Fukushima dai-ichi nuclear power plant [6]**.** The HPCI and SRV are located in each reactor building. However, the EDG, FP, and PI are located in the turbine building.

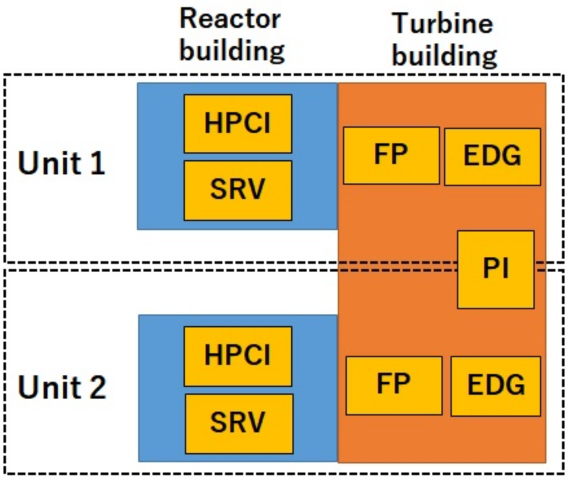


Figure 4. Multi-unit system with two reactors

Figure 5 shows a functional connection of all components in the system of two reactors with a shared system or without a shared system. If the two reactors system is connected via the PI system, it is expected that a power sharing between two units are available when the EDG in one reactor lost its function and another EDG in the neighboring reactor is under operation.
If the HPCI is in the normal state (intact state), it is expected that the core damage is avoided. When the HPCI is lost its function, both the SRV and EDG are required to be in the normal condition to avoid the core damage takes place. If the SRV or EDG or FP lost its function, while the HPCI is in failure state, it is expected that the core damage occurs.
The proximity dependency is considered by assuming that all components located in the turbine building get damaged and lost its function when turbine building is collapsed by an earthquake.
The shared connection is considered by considering a sharing of electricity via the PI. When an electricity is lost in one site, if a power is available in another site, it is expected that the power can be shared to the unit via the PI. If the power sharing process is successive, it will recover the function of the coolant injection system which needs power supply. For simplicity, the power sharing via the PI is always successfully done, when there is a demand and a failure of cables is not considered.

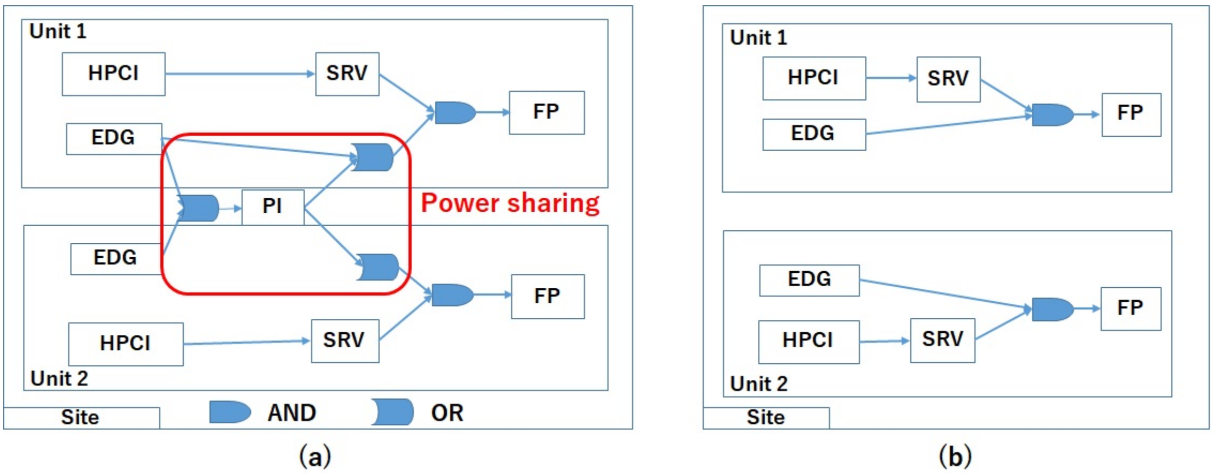


Figure 5. A functional connection of components in multi-unit reactor system (a) with a shared connection and (b) without a shared connection

4.2. Multi-unit dependency evaluation

In order to evaluate an influence of the proximity dependency in the two-unit system, it is assumed that failure rates for 5 components (HPCI, SRV, FP, EDG, and PI) are defined to be consist of inherent part caused by its own failure and common part caused by a common cause failure.
Table 2 shows an initial failure probability (seismic fragility), a probability of failure on demand, and a failure rate (during operation) of the components in the system [7-9]. For the failure on demand, it is assumed that the system state can change once in single time step. For the rate type failure probability, it is considered that the system state can change in every time steps.
The length of each time step was decided 1 min, calculation time is 24 hours (1440 minutes). Since it is expected that 24 hours is enough time for recovery actions to be tried. 100,000 samples were used for Monte Carlo method.
Figure 6 shows calculated failure rates of the HPCI (a) and DG (b) which consider dependency of common cause failure caused by identical component in the other unit. The failure rate of HPCI in unit 1 (HPCI 1) and DG in unit 1(DG 1) were calculated by using Monte Carlo sampling with consideration of the dependency caused by identical component. When the dependency caused by identical component have strong correlation, in other words, the correlation between two unit is 1, the failure rate of HPCI 1 during the operation has the same value with that of HPCI in unit 2. On the other hand, when the correlation is 0, in other words, there is no multi-unit dependency caused by identical component between component in two units, the failure rate does not receive any influence from adjacent unit.

Table 2: Failure rate data used for multi-unit dependency evaluation

	Initial failure probability	Probability of failure on demand	Failure rates
HPCI	2.10E-02	1.40E-02 [1/d]	4.40E-08 [1/h]
SRV	8.10E-06	2.04E-05 [1/d]	0
DG	1.80E-02	1.57E-03 [1/d]	1.42E-04 [1/h]
FP	2.10E-02	1.40E-02 [1/d]	4.4E-08 [1/h]
PI	6.17E-02	2.00E-05 [1/d]	0

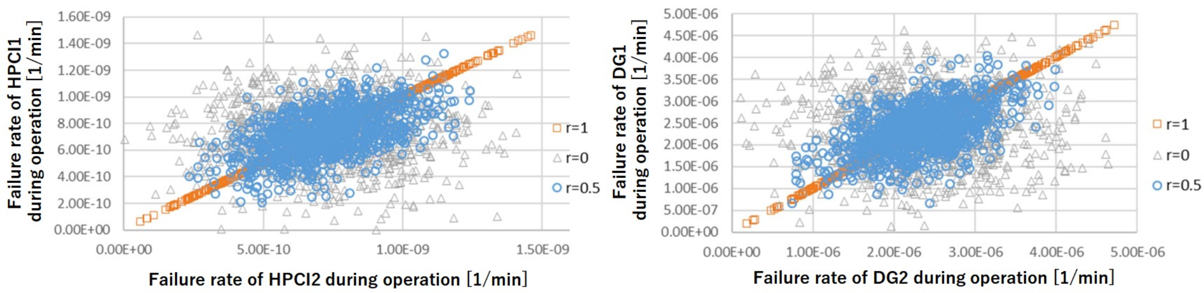


Figure 6 Failure rate of a HPCI and DG with consideration of multi-unit dependency caused by identical component

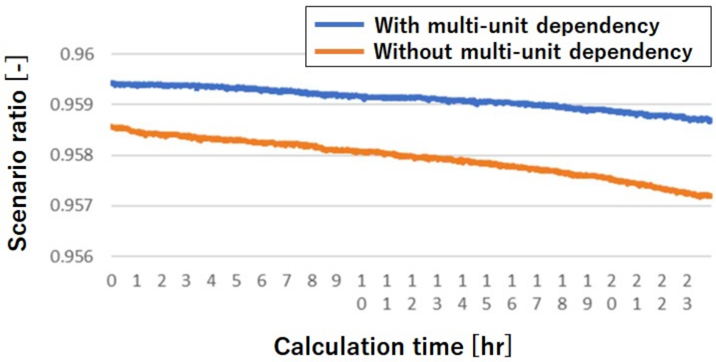
4.3. Accident scenario quantification for multi-unit system

Table 3 shows the result of accident scenario comparison of two-unit system with consideration of the multi-unit dependencies and without dependencies. The fraction of the common cause failure caused by multi-unit dependency was given as 0.5. The total sample number was 100,000.
The results show that the number of calculations which ends with the single unit failure and two units failure are decreased. For single unit failure case, the number decrease 3 %, but for the two unit failure case, 26% of scenario decrease with considering multi-unit dependency. On the other hand, the number of scenarios that both two unit are under the condition of core cooling increases. It indicates that by considering the power sharing via the PI, the recovery of electricity makes avoid the core damage scenario.

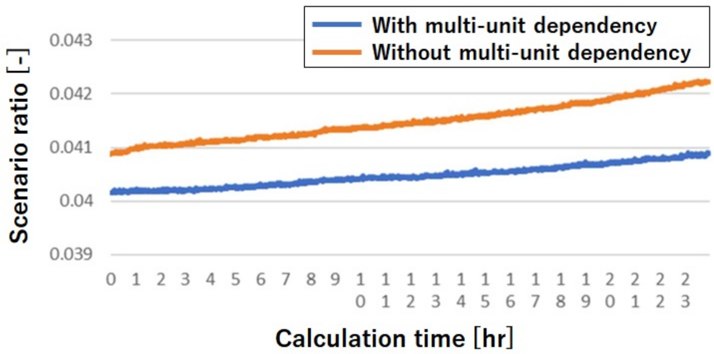
Figure 7 shows, time history of the ratio of accident scenario in case of (a) no core damage, (b) single unit core damage, and, (c) two unit core damage. It shows that the number of no core damage scenario increase but the number of the core damage in single unit and two units decrease with time progression. It is expected that the power sharing via the PI is effective to avoid core damage in multi-unit system. From these results, accident scenario quantification in the mulit-unit scenario

Table 3: Accident quantification analysis in multi-unit system by comparing influence of mulit-unit dependencies

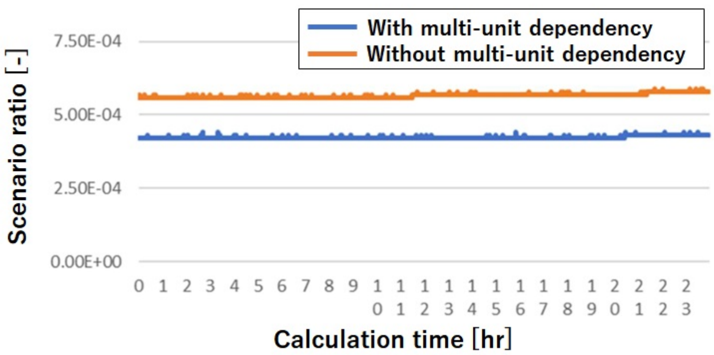
	Without multi-unit dependency	With multi-unit dependency	Transited scenario number	Scenario transition ratio
No failure	0.957	0.958	150	1.001
Single unit core damage	0.042	0.041	-135	0.97
Two units core damage	5.80E-04	4.03E-04	-15	0.74



(a) No core damage



(b) Core damage in single unit



(c) Core damage in two unit

Figure 7 Comparison of time history of number of accident scenario of (a) no core damage, (b) core damage in single unit, and (c) core damage in two units with/without multi-unit dependency consideration

5. CONCLUSION

An evaluation model for quantitative risk assessment in multi-unit site with consideration of multi-unit dependencies. Multi-unit dependencies cause by the initiating event, identical component, proximity, and shared connection are considered to evaluate an influence of multi-unit dependency in accident scenario progression.

The state transition model was used to evaluate system status at each time step of calculation, and the continuous Markov process and Monte Carlo method was adopted to decide the state of system at every time step.

A preliminary analysis considering that the multi-unit dependency can be divided in to inherent part and common cause part of failure rate, was carried out to validate a feasibility of the proposed model. A simple two unit system which has HPCI, SRV, FP, EDG, and PI are used for scenario quantification.

The result of the analysis shows that multi-unit dependency make change in accident progression in multi-unit system. More detailed model which use the Bayesian belief network (BBN) is recommended to be implemented in the proposed model to calculate failure rate more realistically for multi-unit risk assessment.

References

[1] International Atomic Energy Agency, Safety Standards Series No.NS-R-1, Safety of Nuclear Power Plants: Design, Safety Requirements, (2000).

[2] S. Samaddar, K. Hibino and O. Coman, "Technical Approach for Safety Assessment of Multi-Unit NPP Site Subject to External Event", *Proceedings of PSAM12*, Honolulu, Hawaii, (2014)

[3] Tokyo Electric Power Company, Inc, "Description on Technical Capability Related to Installation and Operation of Nuclear Power Plant for Power Generation Related to Change, In Japanese, (2013).

[4] S. Schroer, and M. Modarres, "An event classification schema for evaluating site risk in a multi-unit nuclear power plant probabilistic risk assessment, Reliability engineering and system safety, Vol.117, p.p. 40-51, 2013.

[5] S. Jang, and A.Yamaguchi, "Dynamic scenario quantification for level 2 PRA of sodium-cooled fast reactor based on continuous Markov chain and Monte Carlo method coupled with meta-model of thermal–hydraulic analysis", Journal of nuclear science and technology, Vol.55, No.8, pp. 850-858, 2018

[6] Nuclear and Industrial Safety Agency, "On the technical knowledge of the accident at Fukushima Dai-ichi NPS", 2012 (in Japanese)

[7] Nuclear power plant reliability data system, Central Research Institute of Electric Power, https://nrrc.denken.or.jp/kisnrr/kk/failureRateList.do

[8] Modification of probabilistic safety assessment method for earthquake, Japan Nuclear Energy Safety organization, 2005

[9] Modification of level 2 PSA for seismic event, Japan Nuclear Energy Safety organization, 2005