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Original Article

Study of combinations of site operating states for multi-unit PSA

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ABSTRACT

As Probabilistic Safety Assessments (PSAs) are thoroughly conducted for the Site Operating States (SOSs) for a single unit, multi-unit Probabilistic Safety Assessments (MUPSAs) are ongoing worldwide to address new technical challenges or issues. In South Korea, the determination of the site operating states for a single site requires a logical approach with reasonable assumptions due to the fact that there are 4–8 operating units for each site. This paper suggests a simulation model that gives a reasonable expectation of the site operation states using the Monte-Carlo method as a stochastic approach and deterministic aspects such as operational policies. Statistical hypothesis tests were conducted so that the reliance of the simulation results can be guaranteed. In this study, 7 units of the Kori site were analysed as a case study. The result shows that the fraction of full power for all 7 units is nearly 0.45. For situations when more than two units are not in operation, the highest fraction combination was obtained for Plant Operation State (POS) 8, which is the stage of inspection and repairment. By entering various site operation scenarios, the simulation model can be used for the analysis of other site operation states.

1. Introduction

In nuclear engineering, early studies of Probabilistic Safety Assessment (PSA) models had a base of single units. For single units, in Level 1 PSA models, the considerations included Full Power (or At Power) states [1] and/or Low Power and Shutdown (LPSD) states [2–4]. The consideration for the LPSD states included the Plant Operation States (POSs) which are 15 individual processes for the standard plant in South Korea [5]. There were also studies considering other level of PSA models [6], and Dynamic PSA (DPSA) models [7], which considers the time-by-time interaction. As research process gone further, these individual researches are put all together as an aggregation [8]. In single unit PSA models, both risk and frequency are considered along the modeling process.

Recent studies for PSAs focus on multi-units from the viewpoint of site level [9,10]. The technical viewpoint of Multi-unit PSAs (MUPSAs) is a consideration of the combinations of each unit. Since there are 15 POSs for the standard plant in South Korea and one state of full power, there is a total of 16 operation states that a single plant could have. For multi-units, the amount of Site Operation States (SOSs) increases exponentially. For example, the Kori site, which has 7 units currently operating, has a total of 16^7 combinations, which is about 0.3 billion.

The MUPSA focuses on specific combination, due to the fact that the process of considering every single combination for each SOS may produce a precise result but is inefficient and virtually impossible. The selection of necessary combinations may include some combinations that have high risks and/or large contributions throughout the lifetime of the reactor or site. In the specific combination, the MUPSA considers the frequency and consequence corresponding to the combination. However, in the view of the contribution of each combination throughout the reactor/site lifetime, research considering the contribution of the SOS itself has not been studied further yet. It is possible to used the raw operation data itself, though there are some major issues for this consideration. There are specific plans and strategies that are set for LPSD, i.e. lengths of LPSD set before each are started, strategies to avoid both twin units to be in LPSD, and using the only statistical treatment is not well-fit to reflect these plans. As an alternative, contributions are considered to use the Markov chain models obtained from the raw operation data [11].

This paper suggests a simulation model for the contributions which each SOS could have and gives a representative outcome of an application based on Markov chain, applying the strategies and plans set for LPSD. The outcomes make it able to apply options by PSA engineers' needs and are based on the operation records of the

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Kori site from 1983 to 2019, which can be found on the website of the Korea Institute of Nuclear Safety (KINS) and Korea Hydro & Nuclear Power (KHNP) [12–14]. By applying trend analysis for the data and using the simulation model with various cases, sorting out the combinations that are screened out will be possible, increasing the efficiency for MUPSA.

2. Data collection and conditioning

2.1. Symbols and acronyms

In this work, some terms are used that require explanation. The following terms refer to a single unit.

- "LPSD length" refers to the number of ongoing days for a specific LPSD event. For example, when a specific LPSD starts on March 1st and ends on March 28th, the "LPSD length" is 28 days. The abbreviation is LL.
- "Full Power length" refers to the total number of days between the end of the former LPSD and the start of the latter LPSD. For example, when the former LPSD ends on January 31st and the latter LPSD starts on March 1st, the "Full Power length" is 28 days. The abbreviation is FPL.
- "Unscheduled Trip length" refers to the number of ongoing days of a specific unscheduled trip. For example, when there is a trip on April 1st and the unit recovers on April 10th, the "Unscheduled Trip length" is 10 days. The abbreviation is UTL.
- "No Unscheduled Trip length" refers to the total number of days between the end of the former unscheduled trip and the start of the latter unscheduled trip. In other words, "No Unscheduled Trip length" is the number of days for which there are no unscheduled trips. For example, when there is an unscheduled trip that is fixed and re-operated on January 1st and another unscheduled trip occurs on January 10th, the "No Unscheduled Trip Length" is 10 days. The abbreviation is NUTL.
- "Unscheduled Trip Frequency" refers to the number of unscheduled trips per calendar year. For example, when there are eight trips during eight years, the "Unscheduled Trip Frequency" is 1 $year^{-1}$, where the *year* stands for calendar year. The counts of unscheduled trips are based on the starting day of the unscheduled trip. In other words, when there is an unscheduled trip starting on December 28th, 2000 which ends on January 2nd, 2001, the count is added to the calendar year 2000. The abbreviation is UTF.

Fig. 1 provides a better understanding of the terms.

In Fig. 3, which shows the flow chart of the simulation model in Section 3.3, there are some acronyms that need explanation. The following terms gives information of the acronyms.

OY = Operation years in a calendar year (input constant)
RT = Repeat times (times to repeat the simulation model) (input constant)
NU = Number of units (input constant)
TU = Type of unit (input constant)
OD = Total operation days (constant)
DC = Days passed during operation
LC = Days passed after the last event (most recent trip)
OS = Operation status result (OD × NU)
UTD = Unit type data
OL = Overlap data (3 × 1)

2.2. Necessity of stochastic simulation

Before discussing the data accumulation process and the mechanism of the simulation model, the data used in the simulation model should be explained. The simulation model aims to determine the contributions of each combination of the operation states. In other words, the simulation model can show the future operation status of the unit sets. At this point, simply using the accumulated data from the past is an option. However, this option has some flaws since the operation of nuclear power plants cannot only explained from a deterministic point-of-view only with data from the past.

When the reactor is in the Full Power State, the length of this state is dependent on the lifetime of the fuel rod. The fuel rod is used in a full cycle and then replaced in the LPSD state. Although there is a standard lifetime of the fuel rod, the operation status of the reactor could affect the lifetime of the fuel rod causing it to burn out more quickly or slowly. Also, technology improvements make it possible for the fuel rod to be used longer. These changes which may be essential for determining the FPL will not be able to be applied when the raw data is used as is.

The main reason for LPSD is to change the fuel rod. However, some inspections and adjustments for the reactor are also performed at the same time. While the fuel rod is removed from the reactor, the inspection and adjustment process is proceeded before the new fuel rod is inserted. The steps of refueling are the 15 POSs. The removal and insertion of fuel rods are POS7 and POS9, respectively. The inspection process is POS8. For the 15 POSs, there

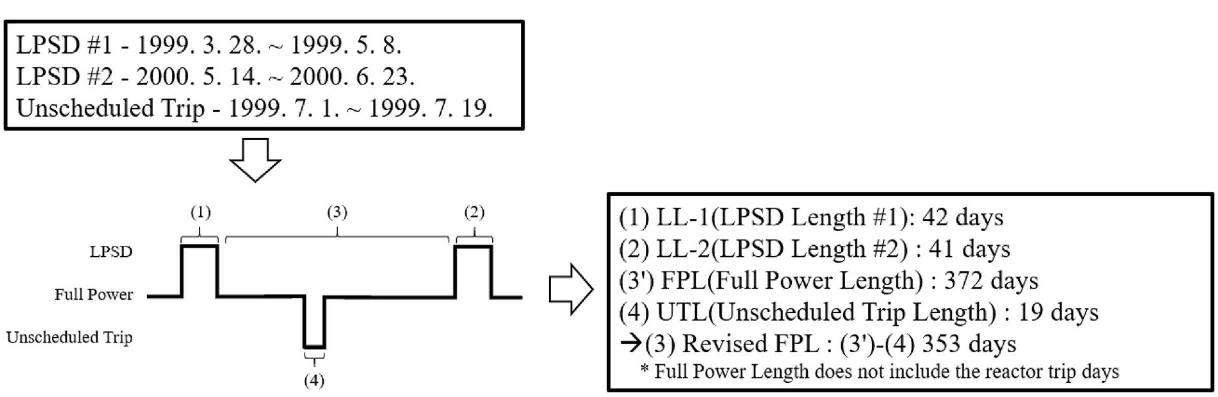

Fig. 1. Examples of the term use.

are standard lengths for a standard plant in South Korea. In the case of POS8, the inspection process causes a large variation of length. Some problems that occur during the POS8 process could cause a variation of length more than data from the past. Similarly, other POSs could have flexible lengths during the process although the variations will not be noticeable compared to POS8.

During the Full Power State, there could be some problems that occur in the reactor, causing unscheduled trips. There are five different reasons of unscheduled trips in South Korea. Situations due to mechanical defections, instrumentation faults, electrical faults, human errors, and natural disasters cannot be predicted simply by deterministic analysis of the raw data. Some incidents must be applied more than the operation data, such as unscheduled trips due to hurricanes that can occur mainly in late summer.

2.3. Data collection

For the simulation model, the Kori site was considered. The data collection process should first be carried out to run the simulation model. Using statistical data from the operation records may not be reliable. However, some other processes will be added to the data and both the reasons for the raw data not being reliable and the added processes will be explained. Table 1 shows the operation status of the Kori site. There are a total of ten units in Kori site. Among the two WH600 unit types, Kori unit 1 was permanently shut down in 2017, while two of the four APR1400 unit types, Shin-kori units 5 and 6 are under construction. The remaining seven units are on operation.

For the ten units at the Kori site, the units in operation are the target of the simulation model. Kori unit 1, which was permanently shut down in 2017, will not be considered in the simulation process. This is because there is no up-to-date data for Kori unit 1 and therefore, we will not be able to show recent trends of the operation status. Shin-Kori units 5 and 6 are currently under construction and are also not treated in the simulation. Therefore, seven units were applied in the simulation model in this study.

The data of the operation records can be found on the KHNP and KINS websites. The operation records that are needed are the start and end dates of LPSD and unscheduled trips. Table 2 shows the results of the data collection. For each unit type, the number of LL, FPL, and UTL observed, and the mean and standard deviation for each length are given. UTF is also given for each unit type.

2.4. Data conditioning

Although the data collected itself can be used in the simulation model, there should be some data conditioning before applying. This process is necessary because of possible outliers that could exist, possible increases/decreases of the data as time passes, and the distributions that the data could have. Fig. 2 shows the data for each unit type in order of time. The x-axis and y-axis for the four graphs represent the days after the commercial operation for each unit started and the length for each event of LL or FPL, respectively. For the WH900 and OPR1000 unit types, there are two units each, which results in an appearance of points gathered.

For the determination of outliers, we could not perform the process for APR1400 due to a lack of data. Also, OPR1000 data does not have a sufficient amount of data. Based on the fact that the APR1400 is an advanced model for OPR1000 and that both unit types have a lot of similarities in their facilities and operation methods, this paper assumes that the data for OPR1000 and APR1400 as a whole.

Outliers are a set as data that are out of the range of the mean and standard deviation of the data. For instance, for WH600 unit types, the mean is 55.44 days and the standard deviation is 42.23 days. Data that are not in the range from 13.21 to 97.67 days are treated as outliers. This range was applied because of possible but extraordinary events that had influences on the lengths, such as the Fukushima accident, which made the LL have a length of over a year for all unit types. As mentioned previously, for the outlier conditioning for the OPR1000 and APR1400 units, which will be referred to as non-WH unit types, the mean and standard deviation for the whole are 136.83 and 48.51, respectively. The data conditioned after removing the outliers is shown in Table 3. Similar to Table 2, the observed number of LL, FPL, and UTL for WH600, WH900, non-WH unit types are given with the mean and standard deviation for each length. UTF is also given for each unit type.

Based on the data shown in Table 3, hypothesis tests were carried out to determine whether there are trends in the data and whether the data follows a specific distribution. For the data of non-WH units, the data is not sufficient for hypothesis testing and is considered to not have a specific trend, following a normal distribution. When there is a trend for the data, the lengths will increase or decrease. This may seem to create a certain problem in which if the simulation model runs for 40 years, the length will increase/decrease to an amount that could not be possible. For instance, when there is a trend of decrease, 40 years of running can cause a LL to have a length of zero. Applying assumptions of upper/lower limits can prevent this, but the application of the limit itself does not have a reasonable explanation. Therefore, the units having a specific trend were treated to follow the recent 5 counts of data, following a normal distribution. Similarly, for the data of non-WH units, the data are not sufficient for hypothesis testing and is considered not to have a specific trend, following a normal distribution.

The statistical hypothesis test of whether the regression line shows a specific trend was first done for WH600 and WH900 units. Test for trend analysis was performed with an F-test to check the null hypothesis (H0) as “No real relationship” expressed mathematically as $MS_{regression} \leq MS_{residual}$. The alternative hypothesis (H1) is set as “Reject null hypothesis” expressed mathematically as $MS_{regression} > MS_{residual}$. The results of the goodness of fit test without outliers for LL and FPL are given in Table 2 within 95% confidence intervals. The mean squares of the regression ($MS_{regression}$) and residual ($MS_{residual}$) are compared in the F-test. Table 4 shows the hypothesis test result for WH600 and WH900 whether the regression line for each shows a trend.

According to the hypothesis test results, not all of the regression lines show a specific trend. Therefore, the next step, which will determine the distributions the data, will be the prior consideration of data conditioning.

The distributions of FPL, LL, UTF, and UTL should be known before conducting the simulation for stochastic modeling. All of the data could be assumed to have normal distributions, but there should be some verification process performed. Goodness of fit tests were carried out for FPL and LL to follow normal distributions,

Table 1
Operation status of the Kori site [15].

Name	Type		Status	First Grid Connection
KORI-1	PWR	WH600	Permanent Shutdown	1977-06-26
KORI-2	PWR	WH600	Operational	1983-04-22
KORI-3	PWR	WH900	Operational	1985-01-22
KORI-4	PWR	WH900	Operational	1985-12-31
SHIN-KORI-1	PWR	OPR1000	Operational	2010-08-04
SHIN-KORI-2	PWR	OPR1000	Operational	2012-01-28
SHIN-KORI-3	PWR	APR1400	Operational	2016-01-15
SHIN-KORI-4	PWR	APR1400	Operational	2019-04-22
SHIN-KORI-5	PWR	APR1400	Under Construction	–
SHIN-KORI-6	PWR	APR1400	Under Construction	–

Table 2
Data of the operation records.

	LL (days)			FPL (days)			UTL (days)			UTF ($year^{-1}$)
	Observed	Mean	Std. dev	Observed	Mean	Std. dev	Observed	Mean	Std. dev	
WH600	16	55.44	42.23	15	418.2	58.96	62	4.55	7.28	1.68
WH900	29	79.17	104.6	27	473.4	27.08	92	3.96	4.66	1.33
OPR1000	18	122.1	101.3	16	471.0	41.81	2	33.50	23.33	0.12
APR1400	2	127.0	48.08	1	517.0	–	1	24.00	–	0.18

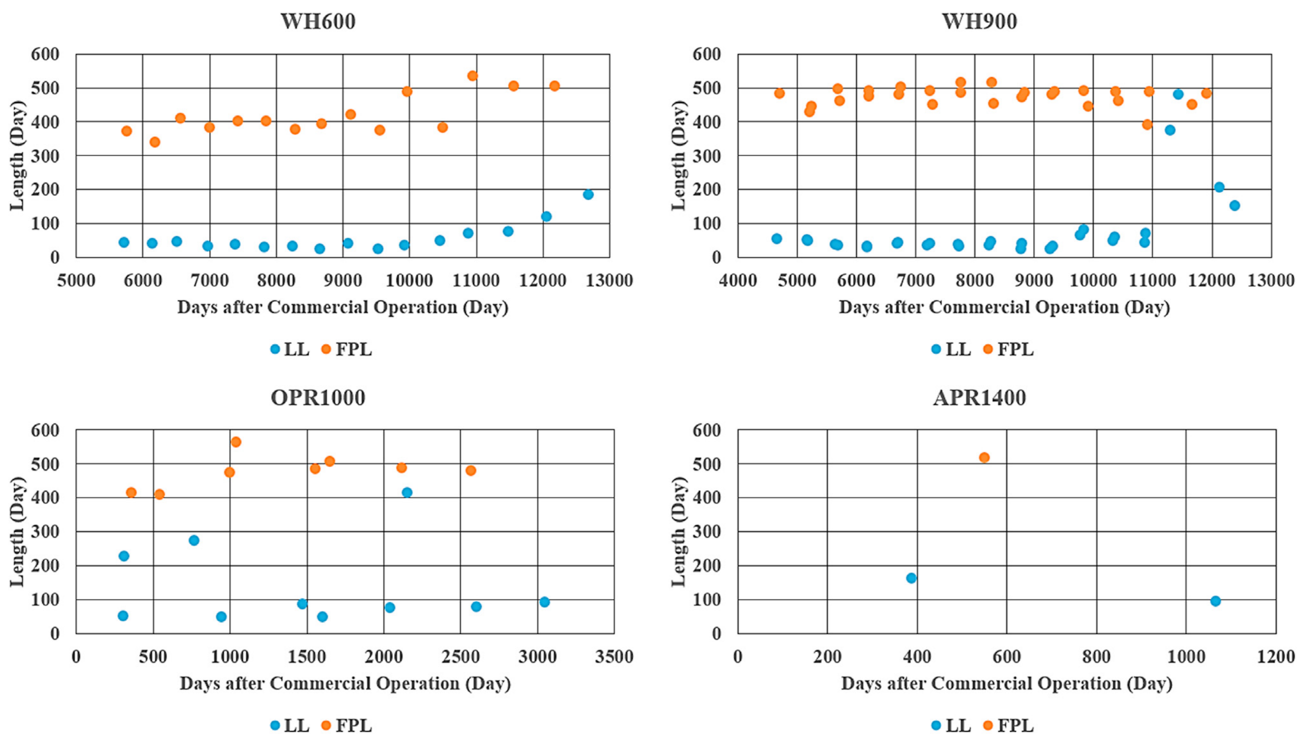

Fig. 2. Scatterplots of the FPL and LL for each unit type.

UTL to follow a lognormal distribution, and UTF to follow an exponential distribution. FPL and LL have standard lengths, which change due to technical or unexpected matters within a certain length boundary. They could be considered to have normal distributions. UTL can also be assumed to have a normal distribution with its mean and standard deviation but the fact that most UTLs are very short can cause issues in which the length distribution can have a negative length. To prevent this, UTL is considered to have a lognormal distribution. UTF, which considers frequency and has an exponential distribution, shows a great result for frequency matters and was chosen for the hypothesis test.

A hypothesis test was conducted as part of the goodness of fit test. The data sets that were tested were grouped by the unit type. In other words, hypothesis tests for the FPL, LL, UTL, and UTF were performed for the WH600, WH900, and non-WH unit types. For FPL and LL, they are considered to follow normal distributions and the chi-square test was performed. The null hypothesis (H0) was set as "The data follows normal distribution ($\chi^2 < \chi^2_{critical}$)". The null hypothesis (H0) for the UTL to follow lognormal distribution is set as "The data follows lognormal distribution," while the null hypothesis (H0) for the UTL is set as "The data follows exponential distribution." The alternative hypothesis (H1) was set as "Reject H0". Table 5 shows the results of the hypothesis tests for each unit type whether they follow normal, lognormal, exponential distribution, respectively.

The data conditioning of APR1400 is the remaining concern. At this point, APR1400 units are considered to have similar results as the OPR1000 units. This is due to the fact that APR1400 is the updated version from OPR1000 and is similar. The results of the data conditioning and the data that will be applied to the simulation model based on the hypothesis tests and adjustments for each unit type are shown in Table 6. The data results show that there is no specific trend for all unit types and length data, while they have a specific distribution for each length data.

3. Algorithm

3.1. Monte-Carlo method

The Monte-Carlo (MC) method is generally used to obtain estimates of solutions of mathematical problems by means of random numbers. This method is used widely for simple situations such as calculating the value of the ratio of the circumference of a circle to its diameter to complicated engineering processes. The random numbers are obtained normally using a roulette-like machine and the random numbers following a specific distribution the user needs can be obtained by applying some adjustments [16].

The data conditioning shows that there could be some variations of the lengths according to the mean and standard deviation. The method used to apply the variations is based on the MC

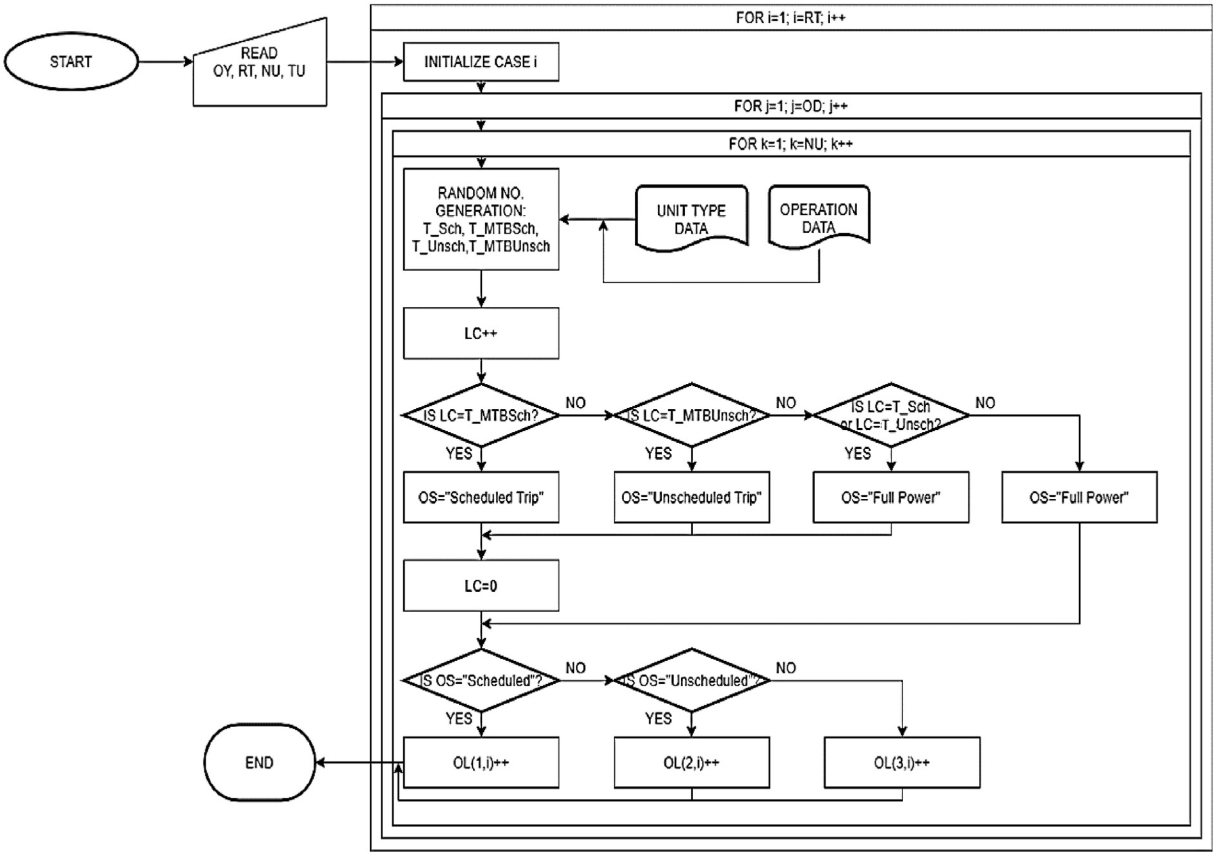

Fig. 3. Flow chart of the simulation model.

Table 3
Operation record data without outliers.

	LL (days)			FPL (days)			UTL (days)			UTF (year^{-1})
	Observed	Mean	Std. dev	Observed	Mean	Std. dev	Observed	Mean	Std. dev	
WH600	13	41.57	15.45	11	399.6	33.00	57	2.86	2.20	1.54
WH900	25	43.28	13.99	20	477.3	14.58	80	2.45	1.76	1.16
Non-WH	9	71	19.59	6	491.0	16.62	3	30.3	17.39	0.14

Table 4
Hypothesis test results for WH600 and WH900.

Hypothesis test	Data	WH600	WH900
Does the regression line show a trend?	LL	Accept H0	Accept H0
H0: $MS_{regression} \leq MS_{residual}$	FPL	Accept H0	Accept H0
H1: Reject H0			

method. By using the MC method, random sampling of computational algorithms is conducted to obtain numerical results for the lengths. These random lengths are used to show a reasonable result for the simulation model.

In the simulation model, random numbers following normal, lognormal, and exponential distributions are applied. Based on the distribution each are assumed to follow according to the hypothesis tests in the former steps, LL and FPL take the values from the normal distribution random number set, while the UTL takes the values from the lognormal distribution. UTF take the values that are sampled from the exponential distribution.

For the case of FPL, corresponding to Kori unit 2, which is applied for the WH600 type, the random numbers are generated according to the mean and standard deviation given in the former processes. However, as time passes, the trend is applied to the mean of the data set.

Table 5
Hypothesis test results for WH600, WH900, OPR1000, and APR1400.

Hypothesis test		Data	WH600	WH900	OPR/APR
H0: $\chi^2 < \chi^2_{critical}$	Is it a normal distribution?	LL	Accept	Accept	Accept
H1: Reject H0		FPL	Accept	Accept	Accept
	Is it a lognormal distribution?	UTL	Accept	Accept	Accept
	Does it follow an exponential distribution?	UTF	Accept	Accept	Accept

Table 6
Analysis of the operation records.

	LL (days)			FPL (days)			UTL (days)			UTF (year^{-1})
	Mean	Std. Dev	Trend	Mean	Std. Dev	Trend	Mean	Std. Dev	Trend	
WH600	41.6	15.45	No	399.6	33.00	No	2.86	2.20	No	1.54
WH900	43.28	13.99	No	477.3	14.58	No	2.45	1.76	No	1.16
Non-WH	71	19.59	No	491.0	16.62	No	30.3	17.39	No	0.14

3.2. Flow chart of the simulation model

Until now, the data applied to the simulation model has been conditioned. The method of the simulation model using the conditioned data is explained by the flow chart given in Fig. 3. As the simulation model starts, the user can insert the operation years (OY), the number of times to repeat (RT), the number of units (NU), and the types of each unit (TU). There are three loops that proceed. The unit type data and operation records from the past data which has been conditioned in the previous processes are used to randomly generate future records of FPL, LL, UTL, and UTF. FPL and LL are repeatedly applied to the time records, while with the UTF, unscheduled trips are also recorded regarding UTL. Based on the time records, the number of units having combinations of POSs are counted day by day.

4. Case study

In PSA model practices, considering the unit types and/or unscheduled trips could vary due to the options given by the PSA engineer. Unit type and unscheduled trip issues are always the main issue. Since there is no exact answer for this problem, for unit type issues, both generic and specific results are granted and considered, and for unscheduled trip issues, various cases are used for sensitivity analysis. Based on the assumptions and adjustments given in the previous processes, the simulation model results for Kori site is given in this section as four cases. Each case considers the most generic or most specific results for unit type data, and gives a range where sensitivity analysis can be practiced for unscheduled trip data based on the assumptions in the previous sections. The parameter choices, which are unit type and the presence of unscheduled trip, are chosen based on the main issues PSA engineers consider. By this way, PSA engineers will be able to obtain reasonable ranges for their options for practice. Fig. 4 is given for a better understanding of the setting of the cases. For the label of each case, the front S and G stands for the specific or generic considerations of unit types, while the latter O and S stands for the off-baseline or baseline considerations of unscheduled trips. In this case, the baseline situation is when unscheduled trips are considered in the simulation model, while the off-baseline situation is when unscheduled trips are assumed to not happen.

Considering every POS combination will produce a more accurate result. However, some POSs have lengths of less than a day, which makes it impossible to analysis the results. Therefore, grouping the POSs is necessary for better insight of the results. The grouping process is performed based on the positioning of the fuel rods. POSs 1–6 are grouped as Group 1 and are in the process of preparing to remove the fuel rods from the reactor vessel. POSs 7–9 are grouped as Group 2. The fuel rods are removed at POS 7 and inspection is done in POS 8 with the process of fixing. The fuel rod is loaded at POS 9. POSs 10–15 are grouped as Group 3. Group 3 is the step to re-operate the plant until full power.

4.1. Case GO: not considering both unit type and unscheduled trip

Case GO does not consider both unit type and unscheduled trips. The unscheduled trip frequency is assumed to be zero for this case. This case contains the most generic data as the result. Fig. 5 shows

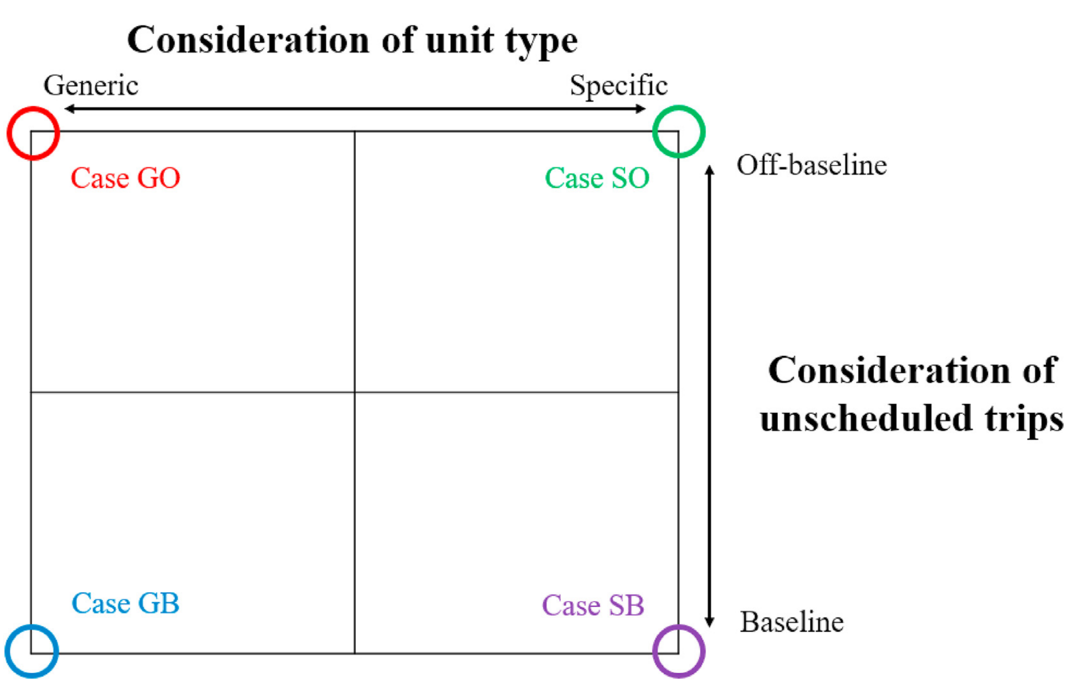

Fig. 4. Case classification.

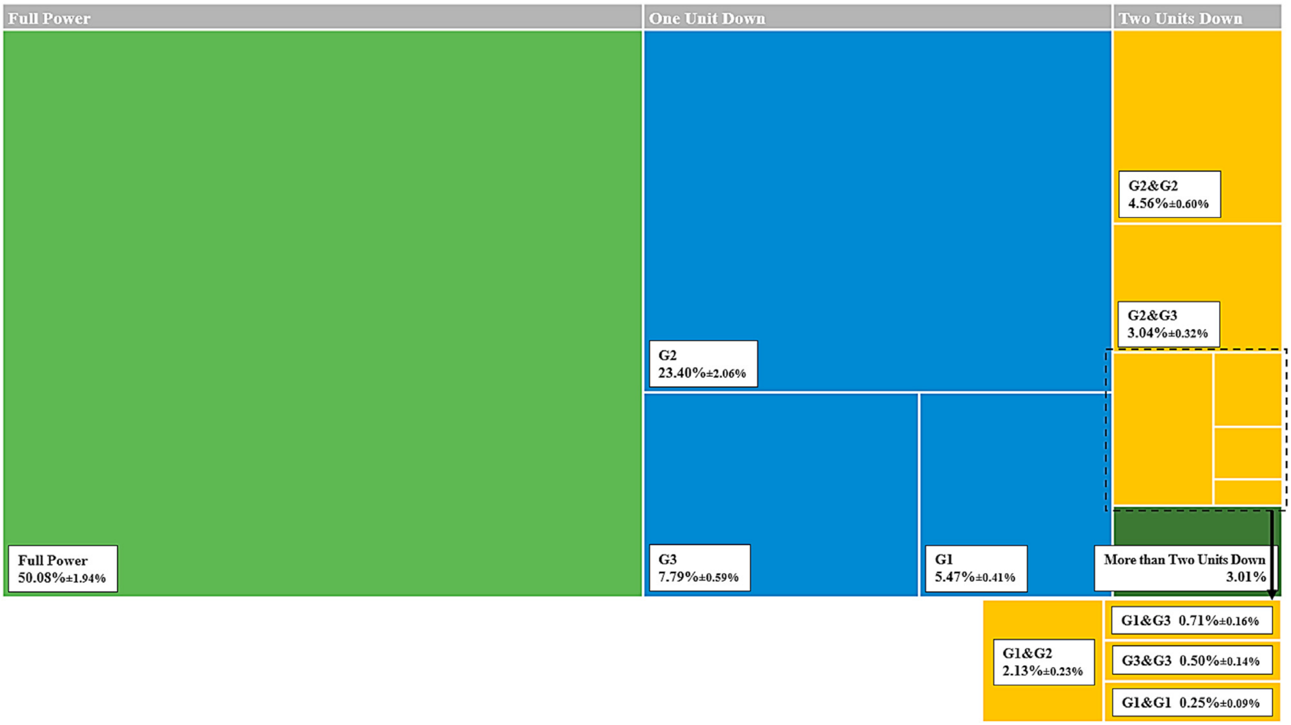

Fig. 5. Result of case GO

Case GO regardless of unit type and not considering unscheduled trips in a treemap graph when the repeat number is 10,000. The standard deviation is lower than one-tenth of the mean for each category, showing that the data has a reliable result. The combination having all eight units in full power are half of the total reactor lifetime. Combinations containing Group 2 has the highest portion when at least one unit is down, roughly 30%. 20% of the lifetime are situations when more than two units are down.

4.2. Case GB: considering only unscheduled trip

Case GB has the unit type data as one set where all data for each unit type is combined. In other words, generic point-of-view for unit type data are given, while specific considerations for

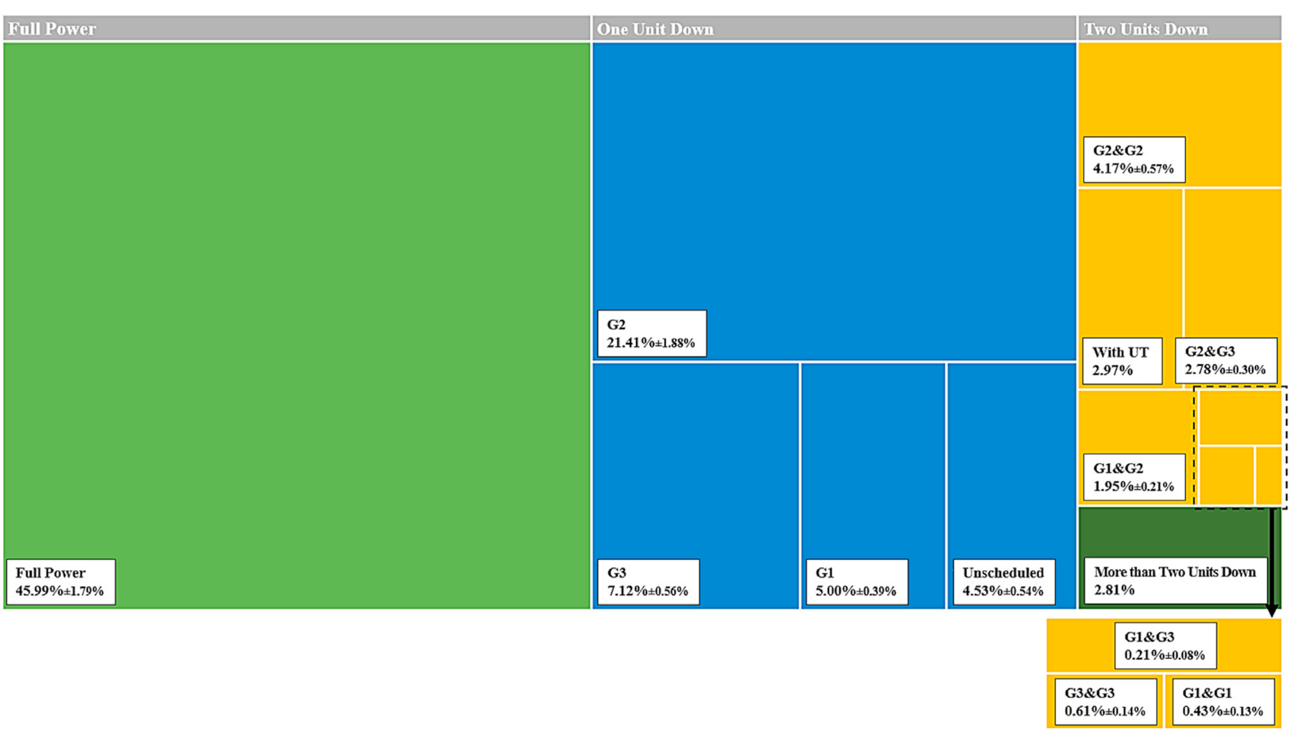

Fig. 6. Result of case GB

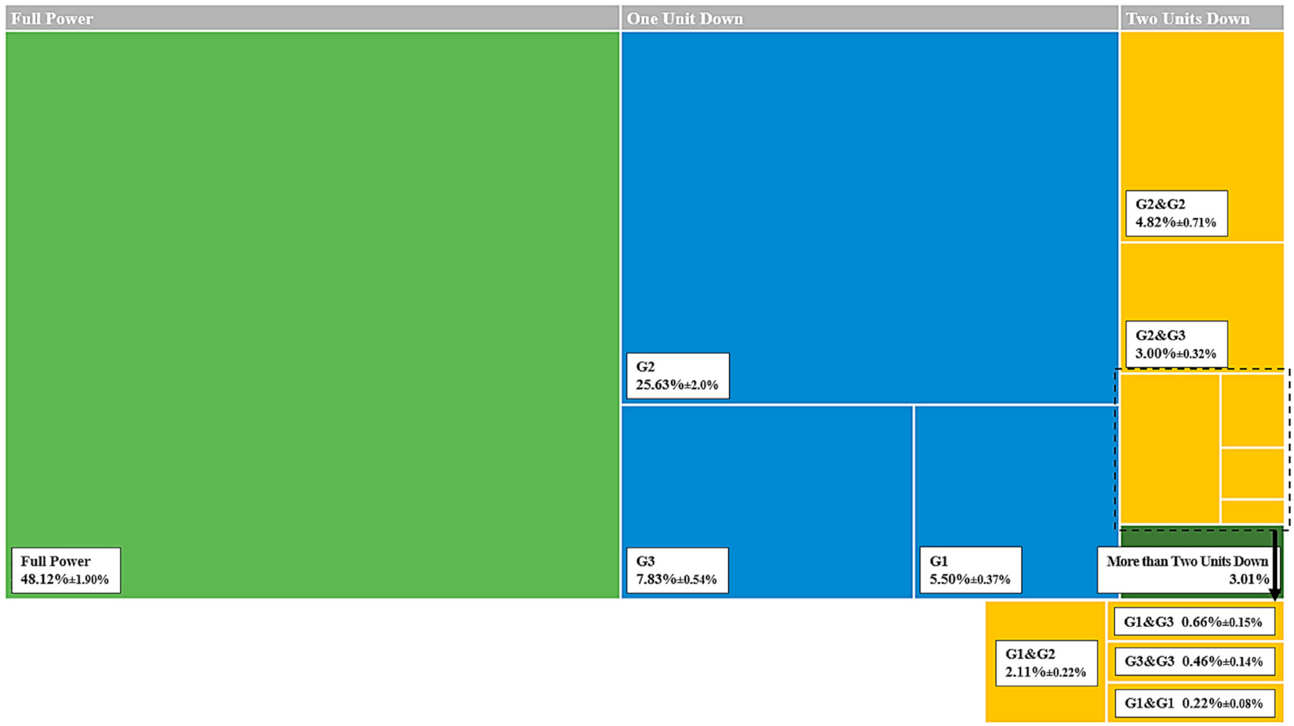

Fig. 7. Result of case SO.

unscheduled trips are applied. Fig. 6 shows the result of Case GB in a treemap graph when the repeat process was 10,000 times. Each category has its label showing the name of the category over the mean and standard deviation data for the area of each category. The standard deviation, which corresponds to the instability of the results, is less than or near to one-tenth of the mean data, which suggests that the data is reliable. In this case, having all units in the full power state has a 45.99% contribution of the entire reactor operation years. The combinations containing Group 2 are the most noticeable. Having one unit down and that unit having the state of Group 2 corresponds to 21.41% of the contribution. Even when two units are down, combinations having Group 2 correspond to nearly 10% of the operation years.

4.3. *Case SO: without unscheduled trips*

Case SO does not consider unscheduled trips, while each unit type is considered. The unscheduled trip frequency is assumed to be zero for this case. The data for unit type data are specific, while the data for unscheduled trip is not considered and assumed to be zero, in other words, generic. Fig. 7 shows Case SO considering the unit type in a treemap graph when the repeat number is 10,000. Again, the standard deviation is lower than one-tenth of the mean for each category, showing that the data has a reliable result. Compared to the data of Case GO, the portion of having all eight units in full power slightly decreases, while the portion containing Group 2 slightly increases. There are no noticeable differences for the portion containing Group 1 and 3.

4.4. *Case SB: consideration of all*

Case SB considers every single contributor that has been introduced until now. Every unit type is considered and unscheduled trips are counted. In other words, both unit type and unscheduled trip considerations are specific. Fig. 8 shows the results of Case SB in a treemap graph when 10,000 is the repeat time. The estimation for the Kori site, which has one WH600 and two WH900 unit types each, and four non-Westinghouse unit types, is given as follows. All units having the state of full power corresponds to 45.26% of the operation years. Having one unit down is roughly one-third of the total years, while having a unit down at the state of Group 2 has the largest contribution. The situation where more than two units down have a noticeable length when regarding Group 2.

As an overall analysis, the cases can be summarized as follows. The percentage of time that all seven units are in the full power state is in the range of 45–50%. Having more than two units down with or without unscheduled trips has a portion of less than 0.05. Situations having units down containing a Group 2 state corresponded to 35–40% of the total reactor lifetime, while having one unit down in the state of Group 2 was roughly 0.25 of the total reactor lifetime. For the comparison of Group 1 and Group 3, combinations considering Group 3 had a slightly larger contribution. Combinations considering unscheduled trips had a percentage of 5–8%.

5. Conclusion

Risk assessment is carried out by the multiplication of frequency and consequence. For each combination of SOSs, the impact of the consequence differs depending on the unit type. Based on the results of this study, the frequency of SOSs can be considered. For the situation where all seven units are in full power, the portion is roughly 0.45, which is a significant amount of the operation years. A reasonable calculation process for the combination of all full power states is necessary for MUPSA projects. The operation state that has the highest contribution with the exception of all full power states is when the state involves Group 2. In particular, having one unit down in the state of Group 2 has a portion of one-fourth. Future research considering this SOS should be performed while studies of the technical issues for the unit sharing facilities with the unit

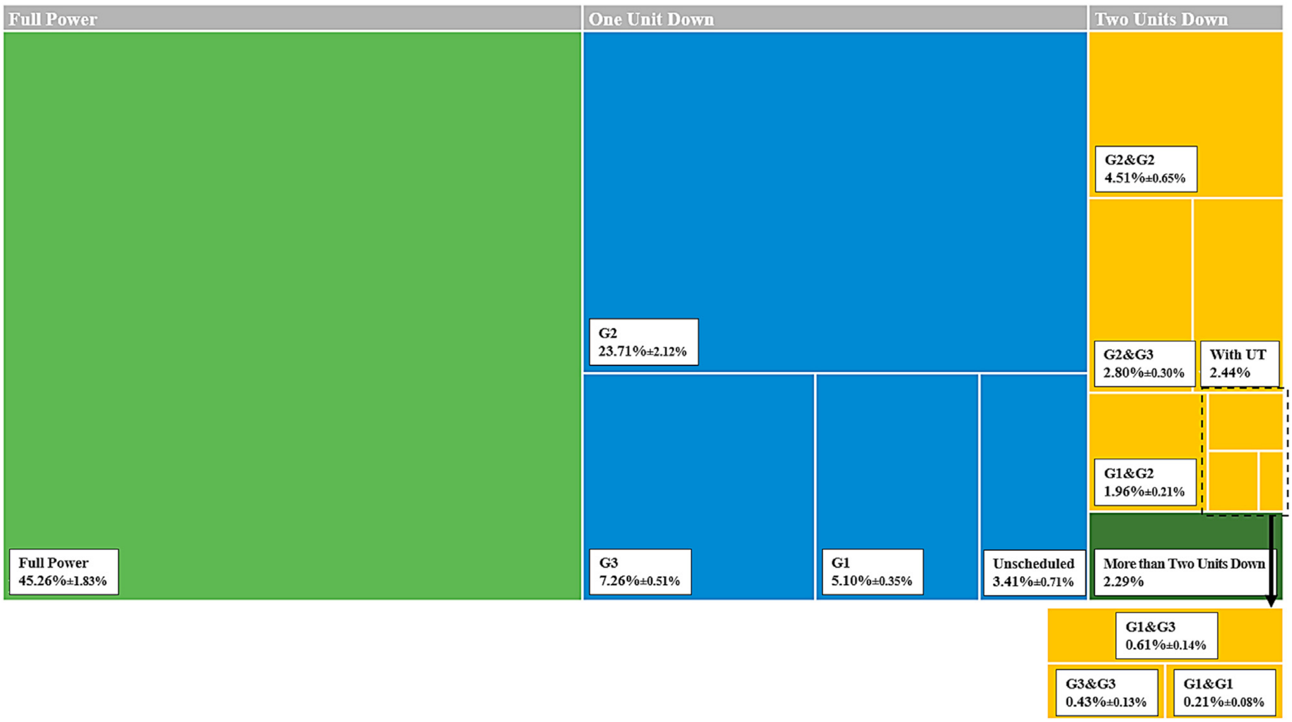

Fig. 8. Results of case SB.

down should also be conducted. For combinations having two units down, the state in which the two units down are all at the state of Group 2 should utilize the prior research process due to its portion. The portion of two units down having an unscheduled trip involved is also noticeable, having the second largest contribution when two units are down. Situations where two units that share facilities experience an unscheduled trip in one unit and a scheduled trip in the other unit could be interesting research for MUPSA projects. Comparing the combinations regarding Groups 1 and 3, the frequencies are similar. However, the consequence for Group 3 is known to be significantly smaller than Group 1 due to less decay heat. Further researches considering Groups 1 and 3 may be able to focus on Group 1 rather than Group 3 as a conservative approach.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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