Simulation Methods of Site Operating States Distribution for Multi-unit PSA

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1. Introduction

In general, PSA(Probabilistic Safety Assessment) models have been developed based on a single unit. Such models usually address a specific operating state including full power or 15 POSs(Plant Operating States) for LPSD(Low Power and Shutdown).

Recently, the MUPSA(Multi-unit PSA) projects are on-going worldwide to capture holistic insights from a viewpoint of site level. One of the technical issues for MUPSA is to arrange the POSs of each unit such that the combination of POSs can be evaluated in the framework of PSA. Since each unit can have one full power state and 15 POSs, there are 16 states total. For combinations of multi-unit states, the amount will increase exponentially. For example, the site which has *n* units will have a combination of 16^n.

In an engineer point-of-view, considering every single combination of POSs is inefficient and even impossible, and selecting important POSs and/or screening combinations of low possibilities are important. This paper suggests a simulation model for the combinations of the operating states of each unit in Kori site, total 8 units including the permanently stopped unit 1, using the operation records during 1983-2019 opening in the website of Korea from KINS(Korea Institute of Nuclear Safety) and KHNP(Korea Hydro & Nuclear Power) [1,2]. By using the simulation model, sorting out combinations so called Site Operating States(SOSs) that are screened out will be possible, increasing efficiency for MUPSA.

2. Methods

2.1. Data Accumulation

The simulation model uses data of scheduled and unscheduled trips and/or overhauls representing the POSs of LPSD for reactor types of WH-600, WH-900, OPR-1000, and APR-1400 in Kori and Shin-Kori site. The data for Kori unit 1, which has been permanently stopped in 2017, is considered in the simulation model, though the data for the unit has not been considered for the data accumulation due to lack of up-to-date data.

There are insufficient data for OPR-1000 and APR-1400 models in this site. For the OPR-1000 data, the data from the same reactor types in Shin-Wolsung site had been added as the supplementary samples. The lack of information for APR-1400, which only can be found in Kori site, will be discussed later with regarding to what kinds of assumptions would be accompanied.

Figure 1 shows the process of the data accumulation.

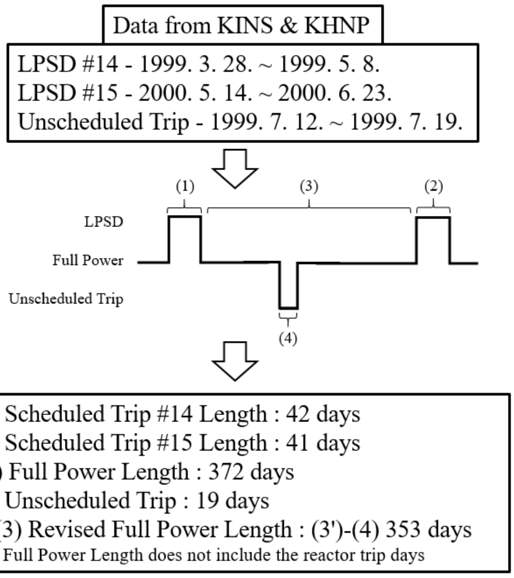


Figure 1. Data Accumulation from Operation Records (Example)

Data accumulated by this method is then summarized in a spreadsheet program and several descriptive statistics are performed. The length of the scheduled trip is the days while the scheduled overhaul is processing, which is the days between the start and the end of the overhaul. Through the descriptive statistics, the average and the standard deviation for each unit's length of the scheduled trip is analyzed. The open-source data providing the operation history is only available for 1999-2019, and the number of the scheduled trips and the operation years in terms of calendar year are referred on this interval.

Some special occasions of scheduled trips have a length over a hundred days. This type of special trips cannot be a part of statistical phenomena. In this study, these special trips are regarded as outliers, but they need to be somehow properly included in the simulation later.

Table I show the mean and standard deviation in terms of days for each type. In case of APR1400, the number of the scheduled trips is too small to quantify the standard deviation.

Table I: Length (days) of Scheduled Trips

	Mean	Sdt. Deviation
WH-600	41.6	15.5
WH-900	43.28	14.0
OPR-1000	64.3	15.6
APR-1400	93	-

The Mean Time Between Scheduled trip (MTBSch) represents the interval between the end of the former trip and the start of the latter trip, which are all scheduled ones. In other words, the MTBSch is the full power length. As mentioned in Figure 1, when there is an unscheduled trip during the MTBSch, the time during unscheduled trip is not treated as the MTBSch. The following data is the mean and the standard deviation of the interval.

Table II: Full Power Length (days)

	Mean	Sdt. Deviation
WH-600	418.2	59.0
WH-900	473.4	27.1
OPR-1000	471	41.8
APR-1400	517	-

For APR-1400, there is only one data for MTBSch so it is unable to obtain a standard deviation.

The unscheduled trip data for Kori site from the operation history is trackable from the beginning of commercial operation for Kori unit 2, 1983. The number of the unscheduled trips and the operation years in calendar year is based on the data from 1983-2019, and the frequency, which represents the number of the unscheduled trips happening per year, is calculated within these data.

For the Westinghouse PWRs, there are a number of repeated trips for a single incident, resulting a significant amount of increase in the number of unscheduled trips. From engineering judgement considering such period belongs as a kind of infant fatality, the early years of operation are screened out. The data in which the outliers or less-relevant datasets are removed is shown in Table III.

Table III: Data of Unscheduled Trips

	Frequency (No. of trips/year)	Length(days)	
		Mean	SD
WH-600	1.68	4.6	7.3*
WH-900	1.33	4.0	4.7*
OPR-1000	0.17	23.2	18.2
APR-1400	0.2	24.0	-

* They are caused by a few extremely delayed unscheduled trips.

Again, APR-1400 only has one unscheduled trip in the operating years of five. Therefore, no standard deviation was found, and using the data of APR-1400 will be discussed in the latter part of the paper.

2.2. Assumptions for establishing simulation model

The objective of the simulation model is to find the combinations of which has a considerable possibility, or to consider the combinations that involves important POSs. Therefore, the simulation model should be able to imitate a designated time interval and repeated counts. The stacked information will then be analyzed to figure out combinations that have a considerable amount of possibility and the frequency of the combinations involving important POSs. For the time interval and repeated counts, the user of the simulation model will be able to insert information as needed. The number and types of units will also be able to be inserted by the user. For the discussions in this paper, the time interval and the repeated counts was designated as 40 years and 1000 times, respectively, while 8 units are designated as WH-600, WH-900, OPR-1000, APR-1400, two units for each.

2.2.1. Insufficient data of APR-1400

There is not much data available for APR-1400 because of relatively short operation history. The cutoff of outlier data even shortens the data more. To replace and backup the data of APR-1400 in the simulation model, the data of OPR-1000 is added. In other words, the data used for APR-1400 is the data from both APR-1400 and OPR-1000. Such kind of assumption is unavoidable at this time but needs to be confirmed by long-term data.

2.2.2. Stochastic modeling

In the simulation model, the data of the length of scheduled and unscheduled trips, MTBSch, and the frequency of the unscheduled trips which corresponds to Mean Time Between Unscheduled trip (MTBUnsch) representing the POSs were assumed to be a random variable, so they should be generated based on the probability distribution suggested from the operation history.

The temporal distributions for all data were assumed to be a normal distribution, except for the MTBUnsch, which was assumed to have a cumulative exponential distribution. By the data of mean and standard deviation from Table 1 and 2 each, it is able to get a random number following normal distribution for the length of scheduled/unscheduled trips and MTBSch, respectively.

For Full Power Length and Scheduled Trip Length, standard lengths are given as 18 months and 40 days, with some minor variations due to the operation status. The minor variations can be shown as the standard lengths having a random number with means and standard deviations for each case. This led to the assumption that the data follows normal distribution.

$$T_{Sch} \sim N(\mu_{Sch}, \sigma_{Sch}) \quad (1)$$
$$T_{MTBSch} \sim N(\mu_{MTBSch}, \sigma_{MTBSch}) \quad (2)$$

For the Unscheduled Trip Length and MTBUnsch, they occur randomly. Assumption for these situations were made to have a normal distribution for unscheduled trip length and exponential distribution for MTBUnsch.

$$T_{Unsch} \sim N(\mu_{Unsch}, \sigma_{Unsch}) \quad (3)$$
$$T_{MTBUnsch} \sim exp(\lambda_{MTBUnsch}) \quad (4)$$

In order to justify the probability distribution of the random variables, further researches for the simulation would be somehow properly needed for more accurate results.

2.2.3. Variation of overhaul length

The length of LPSD varies according to Table I. It is known that the length of LPSD has a standard time, based on the 15 POSs. Although there are some minor differences in the length of each POS for different LPSD times, it is known that the POSs that has the most variation, being the key of the change of length for LPSD, are POS 7-9. This is based on the processes POS 7-9 goes through. POS 7 is when the nuclear fuel is removed from a reactor for replacement. With the nuclear fuel removed, POS 8 goes through the process of inspection of the overall power plant. Based on the inspection plan, the length of POS 8 varies in a large scale. After inspection, the nuclear fuel is inserted at POS 9.

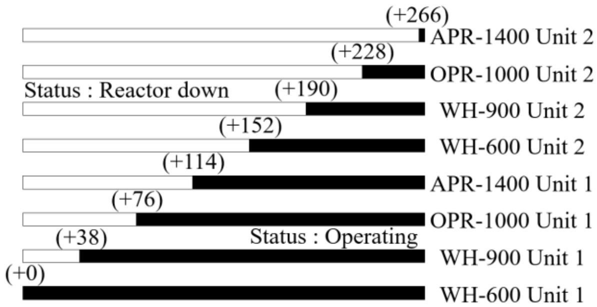
The former setting of POS length change could cause a result of importance only at POS 7-9, having the other combinations to be screened out. Therefore, the simulation model has been set, having three POS groups; group 1 for POS 1-6, group 2 for POS 7-9, and group 3 for POS 10-15. This data set also has the length change only at group 2, which covers POS 7-9, but will be able to have a noticeable result for the other combinations.

For the simulation model, the length of Group 2 is the only probability variable, while the lengths of Group 1 and 3 are fixed values. The length of Group 2 is affected by the Scheduled Trip Length value.

2.2.4. Site configuration

The simulation model is based on the Kori site, which has pair units of WH-600, WH-900, OPR-1000 and APR-1400 each, until unit one of Kori site has been permanently stopped in 2017. Although the information would be able to be inserted by the user, the following discussions in this paper will consider the base of Kori site, having two units of WH-600, WH-900, OPR-1000 and APR-1400, each, regarding the fact that Kori unit one has been permanently stopped.

When operating a nuclear power plant, minimalizing overlaps between units is needed due to economic issues. The simulation model should also consider this matter. To minimize overlaps between units, the start-up of each unit is set differently, with a uniform interval. For this paper, the uniform interval is set as 38 days, which is one-eighth roughly of the MTBSch. Figure 2 shows the initial start-up of the simulation model. As it was mentioned in Figure 1, when there is an unscheduled trip during full power, the unscheduled trip length is not added to the full power length.



* ( ) : Days passed after the initial start-up of the simulation model

Figure 2. Initial Start-up of Units

As such, because there is a policy-related part, not stochastic, we judge that the distribution of SOS should be obtained using simulation methods, rather than a point estimate dependent empirical data.

2.3 Simulation Pseudo Code

The simulation model follows the Pseudo Code in Figure 3.

OY = Operation Years in Calendar Year (input constant)
RT = Times of Repeat (input constant)
NU = Number of Units (input constant)
TU = Type of Units (input constant)
OD = Total Operation days (constant, OY x 365)
DC = Days passed during operation (variable, DC ≤ OD)
LC = Days passed after last event(Trip) (variable)
OS = Operation Status Result (vector, OD x NU)
UTD = Unit Type Data (pre-prepared file(txt))
OL = Overlap Data(vector, 3 x 1)
μ_{Sch}, μ_{MTBSch}, μ_{Unsch} = Mean values for Scheduled Trip Length, MTBSch, Unscheduled Trip Length
σ_{Sch}, σ_{MTBSch}, σ_{Unsch} = Standard Deviation values for Scheduled Trip Length, MTBSch, Unscheduled Trip Length
$\lambda_{MTBUnsch}$ = Frequency of Unscheduled Trip
T_{Sch}, T_{MTBSch}, T_{Unsch}, $T_{MTBUnsch}$ = Days data for Scheduled Trip Length, MTBSch, Unscheduled Trip Length, MTBUnsch

```
Initialize
Insert Data by User
   Read OY, RT, NU, TU
For i=1 to RT
  For j=1 to NU
  Open UTD
     Read μ_Sch(TU), μ_MTBSch(TU), μ_Unsch(TU),
          σ_Sch(TU), σ_MTBSch(TU), σ_Unsch(TU),
          λ_MTBUnsch(TU)
    For k=1 to OD
       T_Sch ~ N(μ_Sch, σ_Sch)
       T_MTBSch ~ N(μ_MTBSch, σ_MTBSch)
       T_Unsch ~ N(μ_Unsch, σ_Unsch)
       T_MTBUnsch ~ exp(λ_MTBUnsch)
       LC++
       If (LC = T_MTBSch)
          OS(k,j) = "Scheduled Trip"
          LC=0
       Else if (LC = T_MTBUnsch)
          OS(k,j) = "Unscheduled Trip"
          LC=0
       Else if (LC = T_Sch or LC = T_Unsch)
          OS(k,j) = "Full Power"
          LC=0
       Else
          OS(k,j) = "Full Power"
       End if
    Next
  Next
  OS -> "Full Power " = 1, "Scheduled Trip" = 2,
          "Unscheduled Trip" = 3
  For x = 1, OD
    For y = 1, 3
      OL(y,1) += Countif (1≤z≤NU, OS(x,z)=y)
    Next
  Next
Next
```

Figure 3. Pseudo Code of Simulation

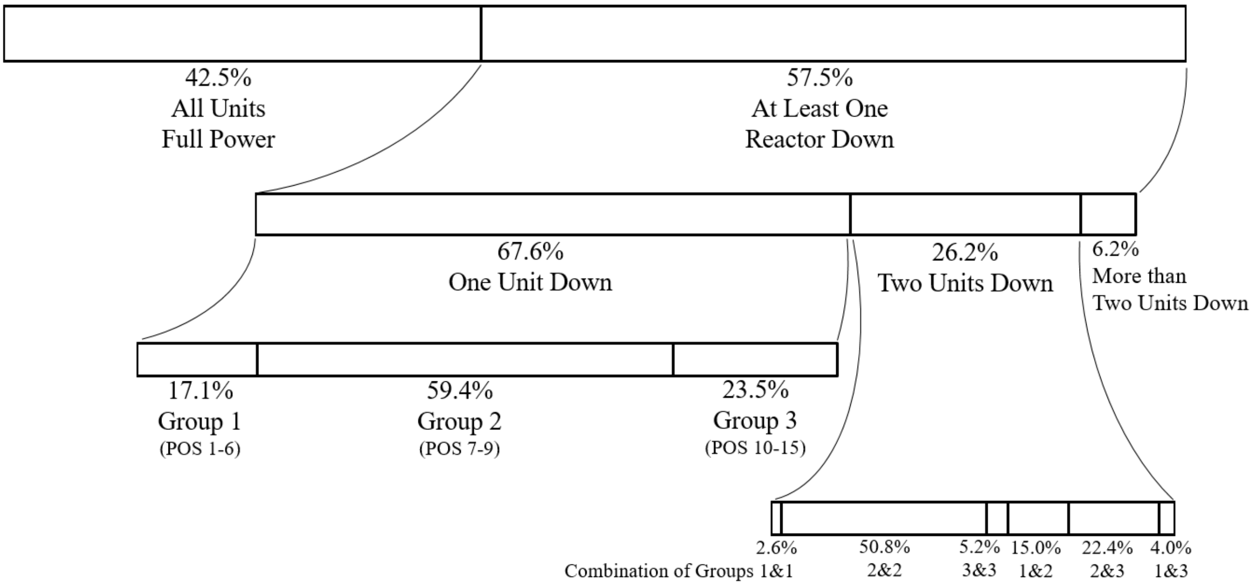


Figure 4. Simulation Model Overall Results

3. Results

3.1 Three group analysis results

The three groups were mentioned in the assumption of LPSD length variation: POS 1~6 for group 1, POS 7~9 for group 2, POS 10~15 for group 3. The overall result of the simulation model is shown at Figure 4.

According to the overall result, the days that the 8 units run in full power is 42.5% of the total operation time. For the times when at least one reactor is down, 26.2% of it has more than two units down. Every bar has 100% in total, and calculations for a particular combination will be possible by this result. For example, suppose a situation calculating the possibility of two units down, which has a combination with two group 1 states. The calculation will be as the followings:

$$\text{Fraction} = 0.575 \times 0.262 \times 0.026 = 0.0039 \quad (5)$$

By the simulation model, it is able to figure out the fractional combinations. When there are two units down, it is most likely to have two Group 2 (2&2) combination. Combinations concerning Group 2 are almost 90% of the time when two units are down. It is shown that Group 2 has the most contribution for the situation where at least one unit is down, roughly a contribution of 70% for the situation.

4. Conclusion

In this paper, simulation methods and some results for determining the combinatorial distribution of SOSs are presented. The simulation method will be available for a variety of purposes since results can be identified by reflecting the operational strategy of the plant site or by changing the assumptions of the probability variables. Especially, the result of this paper shows the possibility that selection of important or high-fractional combinations of SOSs are acceptable when establishing multi-unit PSA models.

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