Multi-Unit Dependency Modeling Based on Reported Japanese Nuclear Power Plant Incidents

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Abstract: Fukushima-Daiichi accident occurred in 2011 highlighted the importance of multi-unit site risks, and particularly underlined possibility of unit-to-unit dependencies. Extending the current common cause parametric method to the multi-unit context has been recognized as a promising solution. A proposed method limited to two or three units at a site is based on finding such dependencies in the U.S. Licensee Event Reports reported to the Nuclear Regulatory Commission (NRC). However, there are many multi-unit sites in the rest of the world with more than three units. Therefore, the framework of the parametric method should be extended to address reactor unit sites with more than three units. The purpose of this study is to discuss an extension of the proposed parametric method applied to the Japanese NPP incident reports in Nuclear Information Archives. This study contributes to the extension of the suggested framework of parametric method for multi-unit PRA and provides insights of unit-to-unit dependencies given the operational experiences in Japan.

Keywords: Multi-Unit PRA, PRA, Unit-to-Unit Dependencies

1. Introduction

Over 80% of operating nuclear power plant (NPP) sites worldwide have more than one reactor units. [1] However, the scope of current PRAs is restricted to single reactor unit models. As such, risks originated from multiple reactor units at a site have not been considered. Also, the risk information derived from these PRAs is with respect to a single unit, not the entire site.

Fukushima-Daiichi accident occurred in 2011 was the first severe accident affecting multiple units due to a single initiating event. As a result, the accident highlighted the importance of multi-unit site risks, and the particularly underlined possibility of unit-to-unit dependencies (e.g. common cause failure across reactor units).

Extending the current parametric method (e.g. alpha factor method [2]) to the multi-unit context has been recognized as a promising solution and there have been many studies of the method, for instance, by Ebisawa et al. [3], Le Duy et al. [4], Modarres et al. [5,6,7]. The proposed method by Modarres et al. is based on the analysis of the U.S. Licensee Event Reports (LERs) [8] (i.e. U.S. nuclear power plant incident occurrences reported by law to the U.S. NRC) and was limited to the NPPs with two or three units at a site. However, there are many multi-unit sites in the rest of the world with more than three units. For example, the maximum number of units in one site in Japan is seven (i.e. the Kashiwazaki-Kariwa NPP site of the Tokyo Electric Power Company). Therefore, the framework of the parametric method should be extended to address the cases beyond three reactor unit sites.

The purpose of this study is to present an extension of the application of the parametric method proposed by Modarres et al. based on Japanese NPP incident reports in the Nuclear Information Archives (NUCIA) [9] in terms of multi-unit sites. This paper consists of the following: Sections 2 describes the parametric estimation method based on the U.S. LERs; Section 3 presents extension of the methodology based on Japanese NPP incidents; Section 4 reports the parametric estimation of multi-unit dependencies based on the Japanese reported NPP incidents; Section 5 offers discussions of the results; Section 6 shows an example application; and Section 7 is the conclusions.

2. Description of the Methodology of Parametric Estimation Based on LERs

In this chapter, the proposed method by Modarres et al. [6, 7] is described. The proposed parametric method estimates the conditional probability of multiple failure events or human errors involving two or three units. The parametric estimation consists of four steps as follows:

1) Identification of the Relevant Multi-Unit LERs
2) Application of Exclusion Criteria
3) Differentiating Common Cause and Causal Events
4) Parametric Estimation of the Multi-Unit Dependencies.

(1) Identification of the Relevant Multi-Unit LERs

The parametric estimation first need to identify the LERs which affected more than one unit. Then, the events are judged from one of the primary apparent *root causes* as follows:

1. Human Action
2. Structure, System, Component Failure or Degradation
3. Organizational Issue
4. Event External to Plant
5. Initiating Event

(2) *Application of Exclusion Criteria*

The multi-unit LERs identified in first steps need to be further screened to identify those with important impact on the multi-unit dependent event parametric estimation. To exclude the events that are not normally considered in the single-unit PRAs, a set of exclusion criteria are applied as follows:

1. Organizational LER events were not considered due to lack of a universally accepted procedure to explicitly model them in the single-unit PRAs.
2. Other events that are not normally considered in the single unit PRAs were eliminated.
3. LERs involving violation of the technical specifications involving multi-units (missed, falsification or incorrect actions) were also eliminated for consideration, if they involved no component degradation or failure events.
4. Design errors with no impact on safety function of equipment or operator actions were eliminated.
5. Events involving software logic faults that did not affect emergency operation of equipment were also excluded.

It should be noted that the organizational events are not considered, but the Schroer's research highlighted the importance of organizational events in both the single and multiple unit risks [5] and showed that they are most significant contributor to the dependent failure events.

(3) *Differentiating Common Cause and Causal Events*

To differentiate the multi-unit events, the end effects of the selected multi-unit LERs in the second stage are subdivided into eleven types of events:

1. Identical human error events in two units
2. Identical human error events in three units
3. Human error event in one unit caused different human error(s) in another unit(s)
4. Identical component failure/degradation events in two units
5. Identical component failure/degradation events in three units
6. Identical initiating events in two units

7. Identical initiating events in three units
8. Initiating events in one unit caused a different initiating event(s) in another unit(s)
9. Component failure/degradation in one unit caused initiating event(s) in another unit(s)
10. Component failure/degradation in one unit caused different component failure/degradation event(s) in another unit(s)
11. Initiating event in one unit caused component failure/degradation event(s) in other units

Therefore, from the reported incidences, the number of occurrences of type-j events involving i units is represented by $n_{i,j}$, where j=1, …,11.

(4) *Parametric Estimation of the Multi-Unit dependencies*

Suppose that the parameters of the parametric model are the fractions of the total probability, $p_{i,j}$, of an event of interest that involves occurrences of type-j events involving i units. The point estimation of $p_{i,j}$ is calculated according to the binomial maximum likelihood estimator:

$$\hat{\boldsymbol{p}}_{\boldsymbol{i,j}} = \frac{\boldsymbol{n}_{\boldsymbol{i,j}}}{\boldsymbol{N}} \tag{1}$$

The variable N, which is the total number of events (LER events in Modarres, et al. study) that actually involved multi-unit site. In identifying it, the following criteria are used:

1. Only events that occurred in sites involving more than a single unit should be considered.
2. Events involving organizational, technical specifications violations should be eliminated.
3. Events may be placed in one of the three categories: initiating event, component failure/degradation and human error.

3. Extension of the Methodology Based on Japanese NPP incidents

In this chapter, the extension of the methodology for multi-unit common cause parametric estimation is discussed based on Japanese NPP incidents using NUCIA.

3.1 Description of NUCIA

In NUCIA, there are 3 kinds of reports: *Trouble Information, Maintenance Quality Information* and *Others Information*. Table 1 shows the description of each report.

Table 1 Description of Reports in NUCIA

Trouble Information	Incidents which legally obligate the plant owners to submit a report
Maintenance Quality Information	Incidents which are advised to be shared with plant owners to improve maintenance activities
Others Information	Events which are not classified into Trouble and Maintenance Information

In this study Trouble Information and Maintenance Quality Information were utilized, which means that Others Information was eliminated. This is because whether “others reports” are reported is largely depend on plant owner’s decision, so including others information may bias the estimated results.

3.2 Extension of Criteria for Identifying Total Number of Events

Reviewing Trouble Information and Maintenance Quality Information, it was found that the criteria for identifying N in Eq. 1 need to be modified as follows.

1. Only events that occurred in sites involving more than a single unit were considered.
2. The events that occurred in other facilities in sites without involving any reactor units were eliminated.
3. The events involving organizational, technical specifications violations were eliminated
4. The events that didn't effect any components in the site units were eliminated.
5. The events were put into one of the categories: initiating event, component failure/degradation and human error.

Note that the second and fourth criteria were added into the original one. Some reports show events which occurred in other facilities (e.g. a facility for waste disposal). This parametric method currently focuses on risks originated from multiple units, not the entire site. That's why the second criteria were added to eliminate the event which occurred in other facilities. The reason the fourth criteria was added is that some event are about worker's injury without any effect on plant operations.

3.3 Extension of Categories of Multi-Unit Events

The proposed eleven categories, which are mentioned in chapter 2 (3), are in case of 2- or 3-unit sites, so in case of more than three unit sites, the categories need to be extended. One way of the extension is to simply add the categories of multi-unit effects, which means that when considering 5-unit sites, the effect (i.e. human error, component failure/degradation and initiating event) in four and five units are added respectively into the original categories. However, this extension would have two problems. One is that the number of events in four or five units would not be sufficient to calculate the probability, which means that the interval of the probability would be too high. The other is that to increase the categories will make it too complicated when multi-unit PRA is being implemented. That's why the effect of more than three units are put together and multi-unit events in case of more than three units are subdivided into fourteen categories as follows:

1. Identical human error events in two units
2. Identical human error events in three units
3. Identical human error events in more than three units
4. Human error event in one unit caused different human error(s) in another unit(s)
5. Identical component failure/degradation events in two units
6. Identical component failure/degradation events in three units
7. Identical component failure/degradation events in more than three units
8. Identical initiating events in two units
9. Identical initiating events in three units
10. Identical initiating events in more than three units
11. Initiating events in one unit caused a different initiating event(s) in another unit(s)
12. Component failure/degradation in one unit caused initiating event(s) in another unit(s)
13. Component failure/degradation in one unit caused different component failure/degradation event(s) in another unit(s)
14. Initiating event in one unit caused component failure/degradation event(s) in other units

4. Parametric Estimation Based on NUCIA

Again, in this study Trouble Information and Maintenance Quality Information were utilized. In order to estimate the parameters of unit-to-unit dependencies, the reports of Trouble Information and Maintenance Quality Information in NUCIA submitted from 2000 to 2011 were analyzed.
The total number of reports is 1708 and a subset of 1587 events were identified as occurring in multi-unit sites concurrently. Examining these 1587 reports, it is identified that 91 of these reports affected more than one unit. Then, applying to the exclusion criteria, which is mentioned in chapter 2 (2), 26 reports of the identified 91 reports were eliminated, 19 reports were eliminated because these are organizational events (the first criteria) and 7 reports were eliminated based on the consideration of the exclusion criteria 2 through 5. Therefore, 65 reports remained and used for estimating multi-unit dependent event probabilistic parameters. To differentiate the multi-unit events, the 65 reports were divided into the categories which are mentioned in Section 3.3.

The variable N, which is the denominator in Eq. (1), was also identified. Table2 shows the number of events occurred in multi-unit sites based on the extended criteria mentioned in Section 3.2.

Table 2 total number of events occurred in multi-unit sites

Event Description	Number of events for 2- or more unit sites	Number of events for 3- or more unit sites	Number of events for 4- or more unit sites
Initiating Events	138	111	79
Component failure/Degradation	1041	874	610
Human Error	129	110	85
Total	1308	1095	774

A total of 279 events were eliminated based on the consideration of the extended criteria and 1308 events remained. Then the probabilities of parameters for multi-unit dependent events were estimated. The result of the parametric estimation is shown in Table 3. The number of events, $n_{i,j}$, is shown in the third column of Table 3. For example, the number of identical human error in two units is one. When estimating the probability of the event, 129, which is shown as the number of human error events in two or more unit sites, were used as the denominator (i.e. N=129) in Eq. (1). In case of identical human error in more than three units, N=85 was used as the denominator. As such, the point estimate of the probability represented in the fourth column of the Table 3 was estimated. The confidence intervals of the true $p_{i,j}$, which is shown in fifth column of the Table 3, are evaluated using the conjugate Bayesian estimation of $p_{i,j}$ with the Jeffrey's non-informative prior and assuming that the beta distribution represents the random variable $p_{i,j}$ [6].

5. Discussion

As the Table 2 shows, the proportion of the component failure/degradation is about 80%. On the other hand, the proportion based on LERs is about 57%. This is because in this research the 1587 reports were analyzed and 1392 reports of the analyzed reports (i.e. about 88%) were the events in Maintenance Quantification Information and the only 195 reports were the events in Trouble Information.

As the Table 3 shows, the probabilities of multi-unit events don't become less with the increase of the number of units, which means that in case of identical initiating event, the number of the events in two units is less than that in more than three units. This is because the ratio of external events (especially earthquake) in reported Japanese incident reports is higher than that in U.S. In Schroer's research [6], only one event [10] of the LER events of years 2000 – 2011, which equals to 4207 events, involved an earthquake (i.e. the August 23, 2011 earthquake in Mineral Springs, VA that affected the North Anna Plant that led to a dual unit reactor trip and subsequent engineering safety features actuations). On the other hand, 12 reports of the 65 multi-unit events in Japan involved an earthquake. For example, the Niigata-Ken Chuetsu-Oki earthquake (16 July 2007, Japan) affected the Kashiwazaki-Kariwa nuclear power plants, and the Great East Japan Earthquake (11, March 2011, Japan) led to a simultaneous reactor trip of nuclear power plants of Fukushima Dai-ichi, Fukushima Dai-ni, Onagawa.

It is therefore concluded that the external events, especially seismic events, are very significant in multi-unit PRA. But in this research, the conditional probability of the any event were considered. The further research would be needed, but some studies suggest the possible solution for the seismic events in multi-unit PRA, for instance, by Zhou et al [11], Hakata [12] and Ebisawa et al [13].

Table 3 parametric estimation of probabilities of multi-unit events

Type of Events, j	Events Categorization	Number of occurences of type j events involving i units, $n_{i,j}$	Point Estimate of the probability of the event, $\hat{p}_{i,j}$	the 95% posterior Bayesian interval for $p_{i,j}$
1	Identical Human Error Events in two units	1	0.008	(8.4E-04; 3.6E-02)
2	Identical Human Error Events in three units	0	0	(4.5E-06; 2.3E-02)
3	Identical Human Error Events in more than three units	1	0.012	(1.3E-03; 5.4E-02)
4	Human Error Events in one unit caused different human error(s) in other unit(s)	0	0	(3.8E-06; 1.9E-02)
5	Identical Component failure/degradation events in two units	37	0.036	(2.6E-02; 4.8E-02)
6	Identical Component failure/degradation events in three units	6	0.007	(2.3E-02; 1.1E-01)
7	Identical Component failure/degradation events in more than three units	9	0.015	(5.4E-02; 1.8E-01)
8	Identical Initiating Events in two units	3	0.022	(6.2E-03; 5.7E-02)
9	Identical Initiating Events in three units	1	0.009	(9.7E-04; 4.1E-02)
10	Identical Initiating Events in more than three units	4	0.051	(1.7E-02; 1.2E-01)
11	Initiating events in one unit caused a different initiating event(s) in other unit(s)	0	0	(3.6E-06, 1.8E-02)
12	Component failure/degradation in one unit caused initiating event(s) in other unit(s)	0	0	(4.7E-07; 2.4E-03)
13	Component failure/degradation in one unit caused different component failure/degradation	2	0.002	(4.0E-04; 6.1E-03)
14	Initiating event in one unit caused component failure/degradation event(s) in other unit(s)	1	0.007	(7.8E-04; 3.3E-02)

6. Example Application

In this section, the example application of the parametric method is shown. Suppose that there is one component at a reactor unit with similar components in other units. Assume the marginal failure probability of 0.05 on demand for this component. Three cases are considered as the following:

1. Two unit case
2. Three unit case
3. Four unit case

Then, the joint failure probabilities of all components with and without multi-unit effect (i.e. the independent case) are compared.

6.1 Two Unit Cases

When the component A and B are independent, the joint failure probability can be easily calculated as 2.5×10^{-3}. When the components are dependent, the joint failure probability can be calculated by using the result of parametric estimation in the Table 3. For example, the probability of Pr (AB) given one component failing (e.g. component A) is expressed as Pr (AB) = Pr(A)Pr(B|A). the conditional probability Pr(B|A) can be obtained from the parametric value of type-5 event in the Table 3, which is Pr(B|A) = 0.036. Then the joint failure probability turns to be 5.92×10^{-3}. This means an increase of a factor is 2.4 compared with the independent case.

6.2 Three Unit Case

When the three components are independent, the joint failure probability is 1.25×10^{-4}. If the components are dependent, the joint failure probability can be calculated by using the parametric value of type-5 and type-6 event in the Table 3, as 1.42×10^{-3}, which an increase of a factor of 11.3 when compared with the independent case.

6.3 Four Unit Case

When the four components are independent, the joint failure probability can be simply calculated as 6.25×10^{-6}. When the components are dependent, the joint failure probability can be calculated by considering the conditional probability of type-5, type-6 and type-7 events and would be 3.09×10^{-3}, which is the increase of a factor of 495.

The more the number of units are considered, the bigger the impact of multi-unit dependency would be. This implies that the risks originated from the more number of units would be very significant in multi-unit PRA.

7. Conclusion

In this paper, the extension of the parametric estimation proposed by Modarres et al. [6, 7] was discussed based on the reported Japanese NPP incidents using NUCIA. The extension allowed applications of the results to multi-unit PRA of sites having more than three units. Then the reported Japanese NPP incident reports were analyzed and the extended parameters for unit-to-unit dependencies in multi-unit PRA were estimated. The estimated parameters were also used in a conceptual example to show their applications and the result implies the significance of risks originated from the more number of units. The effects of dependencies on the site risk increases as the number of units placed on a site increases.

References

[1] S. Samaddar, K. Hibino and O. Coman, "*Technical Approach for Safety Assessment of Multi-Unit NPP Sites Subject To External Events*," Proceedings of PSAM12, Honolulu, Hawaii, 2014
[2] U.S. Nuclear Regulatory Commission, "*Guidelines on Modeling Common-Cause Failures in Probabilistic Risk Assessment (NUREG/CR-5485),*" 1998
[3] K. Ebisawa, T. Teragaki, S. Nomura, H. Abe, M. Shigemori and M. Shimamoto "*Concept and methodology for evaluating core damage frequency considering failure correlation at multi units and sites and its application,*" Nuclear Engineering and Design, 288,82-97, 2015
[4] T.D. Duy and D. Vasseur "*A practical methodology for modelling and estimation of Common Cause Failure Parameters in multi-unit nuclear PSA model,*" Reliability Engineering and System Safety, 2017
[5] 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, 117, 40-51, 2013
[6] M. Modarres, T. Zhou and M. Massoud "*Advances in multi-unit nuclear power plant probabilistic risk assessment*," Reliability Engineering and System Safety, 157, 87-100, 2017
[7] T. Zhou, M. Modarres, "*PARAMETRIC ESTIMATION OF MULTI-UNIT DEPENDENCIES*," International Topical Meeting on Probabilistic Safety Assessment and Analysis 2017 (PSA2017), Pittsburgh, PA, 2017
[8] U.S. Nuclear Regulatory Commission, 10CFR 50.73 Licensee event report system, Search Website: https://lersearch.inl.gov/LERSearchCriteria.aspx.
[9] Japan Nuclear Safety Institute, Nuclear Information Archives, Search Website: http://www.nucia.jp/nucia/kn/KnTroubleSearch.do?reSearchFlg=1 (In Japanese)
[10] North Anna Power Station, Letter to the U.S. Nuclear Regulatory Commission, Licensee event report 2011-003-00, 2011
[11] T. Zhou, M. Modarres and E. L. Droguett, "*An improved multi-unit nuclear power plant seismic probabilistic risk assessment approach,*" Reliability Engineering and System Safety, 171, 34-47, 2018
[12] T. Hakata, "*Seismic PSA method of multiple nuclear power plants in a site,*" Reliability Engineering and System Safety 92, 883-894, 2007
[13] K. Ebisawa, T. Teragaki, S. Nomura, H. Abe, M. Shigemori and M. Shimamoto, "*Concept and methodology for evaluating core damage frequency considering failure correlation at multi units and sites and its application,*" Nuclear Engineering and Design, 288, 82-97, 2015