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An Index for Representing Dependencies of Multiple NPPs at a Site

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1. Introduction

One of the key objectives of MUPSA(Multi-unit Probabilistic Safety Assessment) is to assess how much risk increases due to dependencies among units compared to the one when they are completely independent. While SCDF(Site Core Damage Frequency) has been proposed to explain a result of MUPSA [1-2], there are needs for an indicator that reasonably express the level of 'dependency' of multiple units. IAEA [1] has suggested the CPMA(Conditional Probability of a Multi-unit Accident) indicating the ratio of multi-unit CDF in total CDF of a specific unit.

Sharing the motivation above, authors attempted to propose the SDI(Site Dependence Index) to represent the inter-dependency of the whole units in a site in the previous study [3]. The concept of SDI was borrowed from BSI(Banking Stability Index) in financial engineering [4], and SDI is evaluated from the summation of individual core damage probability divided by the probability that at least one unit has a core damage. This index provides a value from *"1"* when units are completely independent (minimum) to *"n"* when units are completely dependent (maximum) for n units. It means the expected number of units that has a core damage when at least one unit has a core damage.

In this paper, authors tried to explain how SDI is different from CPMA with the features of the SDI. Each index was calculated at a component level in order to facilitate understanding and calculation, but the basic concept is not limited such that, any plant level can use the same approach.

2. Dependency Index

2.1 Conditional Probability of a Multi-unit Accident

CDF has been used as a risk metric in level 1 PSA so far and SCDF has been proposed to address the results of level 1 MUPSA. Unlike the single unit PSA, it is necessary to evaluate not only core damage frequency across a site but also the level of dependency in a site to fully understand the risk of multiple units. IAEA [1] has suggested an index called CPMA for representing dependencies of a unit. CPMA is identified as the conditional probability of multi-unit core damage to a specified unit on a site. In other words, CPMA is given by *Pr(more than 2 units fail | specified unit fails)*.

For 3 identical units (A/B/C) at a site, the CPMA of unit A (U_A) can be calculated from the following equation.

$$CPMA\ (U_A) = \frac{2CDF_2 + CDF_3}{CDF_1 + 2CDF_2 + CDF_3} \quad (1)$$

Where CDF_1 is a 1-unit core damage frequency, CDF_2 and CDF_3 is a 2-unit/3-unit core damage frequency, respectively. Fig. 1 shows the Venn diagram of CPMA of unit A. According to [1], SCDF belongs to a site, whereas CPMA focuses on a unit.

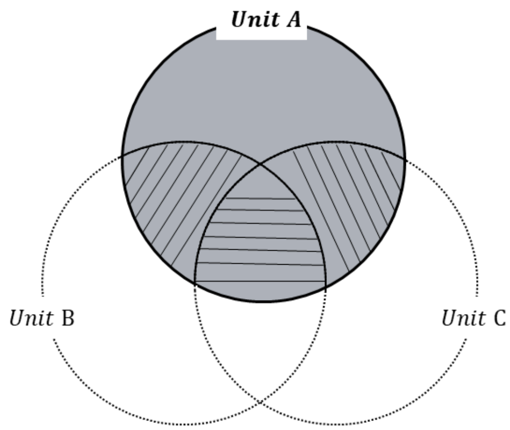

Fig. 1. Venn diagram for CPMA of unit A

As shown in Eq. (1) or Fig. 1, it is a useful index for indicating the dependency level of a particular unit but CPMA is limited to the conditional probability of a specific single unit, not to the entire units. If all units are not identical, we need to calculate CPMAs for unit A, B, and C, respectively, and their aggregation from the viewpoint of a site may not be easy.

2.2 Site Dependency Index

The previous study [3] has suggested an index for site dependency, which can be considered as an extension of the conventional CPMA. The main concept of the SDI is the same as the BSI in financial engineering [4]. BSI is defined as the expected number of distressed banks when at least one bank becomes distressed. Based on this concept, the probability that banks become distressed in BSI can be assumed as the probability of core damage of nuclear power plants in SDI. In other words, SDI is given by *Pr(each unit fails | at least one unit fails).* Compared to section 2.1, CPMA covers multiple failures with focus on individual specific plant, whereas SDI deals with total failures from the viewpoint of a site. For n units, SDI at a site is represented in Eq. (2).

$$SDI = \frac{P(U_1)+P(U_2)+\cdots+P(U_n)}{P(U_1 \cup U_2 \cup \ldots \cup U_n)} \quad (2)$$

Where $P(U_k)$ is a core damage probability of kth unit. Therefore, the meaning of SDI is that the expected number of units involving core damage given that at least one unit has core damage. The Venn diagram for SDI is shown in Fig. 2. Because this Venn diagram covers the entire units unlike Fig. 1, it is possible to express the dependency across a site or between units according to the Eq. (2). If the SDI for unit A and B is needed, the Eq. (2) can be modified as follows:

$$SDI_{AB} = \frac{P(U_A)+P(U_B)}{P(U_A \cup U_B)} \quad (3)$$

As the dependency increases, the hatched area is equal to the gray area in Fig. 2. According to Eq. (2), the SDI of n units is close to "*n*". It means that if at least one unit suffers from a core damage then all units will have core damages. On the other hand, the denominator is equal to the numerator in Eq. (2) when all units are independent. Therefore, the SDI has a value of "*1*". In this case, even if core damage occurs at any unit, only 1 unit will suffer from a core damage. Furthermore, it is easy to obtain the SDI because the separation of the independent and dependent failures is not required.

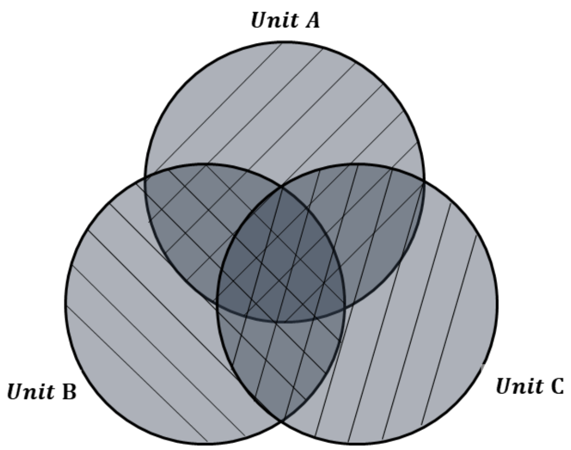

Fig. 2. Venn diagram for SDI of a site

3. Case Study

The case study demonstrates how SDI works and compares the results of SDI and CPMA with simple examples at a component level. This is able to be extended to evaluate the dependencies at a plant level. The failure probability of the components in this case study will be conditional core damage probability in the plant level.

Table I represents the minimal cut sets of 3 components (A/B/C) with CCFs(Common Cause Failures).

TABLE I: Minimal cut sets: 3 components failure with CCF

	Minimal cut sets
P(A)	$Q_1^A + Q_2^{AB} + Q_2^{AC} + Q_3^{ABC}$
P(A ∪ B)	$Q_1^A + Q_1^B + Q_2^{AB} + Q_2^{AC} + Q_2^{BC} + Q_3^{ABC}$
P(A ∪ B ∪ C)	$Q_1^A + Q_1^B + Q_1^C + Q_2^{AB} + Q_2^{AC} + Q_2^{BC} + Q_3^{ABC}$

Where Q_1^A is a failure probability due to an independent failure of component A and Q_2^{AB} is a two component (A and B) failure probability due to CCFs. In order to quantify the minimal cut sets in Table I, the total failure probability (Q_T) and CCF factors (f_k) for k failures are required. The CCF factors can be alpha factor or beta factor. In this paper, the total failure probability was assumed to be 3.0E-02 for demand failure and CCF factors in Table II was used to quantify the minimal cut sets in Table I.

TABLE II: CCF factors used in the case study

	Case 1*	Case 2	Case 3	Case 4	Case 5	Case 6**
f_1	1	0.95	0.9	0.7	0.2	0
f_2	0	0.04	0.07	0.2	0.3	0
f_3	0	0.01	0.03	0.1	0.5	1

* Case 1: Completely independent
** Case 6: Completely dependent

For example, case 1 indicates that all components are completely independent because the CCF factor for 2 and 3 components failure is zero. On the other hand, case 6 includes a fully dependent condition of all components. The level of dependency of components is varied depending on the cases.

If all components are identical, Q_1^A can be calculated by $f_1 \times Q_T$ and $Q_2^{AB} = f_2 \times Q_T$. Table III shows the results of SDI and CPMA based on Table I and II.

Table III: SDI & CPMA based on Table I and II

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
SDI	1.000	1.047	1.092	1.286	1.950	3.000
CPMA	0.000	0.087	0.159	0.417	0.846	1.000

The results in Table III were calculated on the assumption that all components are identical (or symmetric). For a more detailed comparison, the SDI for the case 4 was represented as follows:

$$\mathrm{SDI}_{\mathrm{Case\ 4}} = \frac{P(A)+P(B)+P(C)}{P(A \cup B \cup C)} = 1.286 \quad (4)$$

The result of the SDI for the case 4 can be interpreted that if each component has such degree of dependency (such as CCF factors in case 4), about 1.286 components will fail once one component fails. For the same case, the CPMA of the component A can be calculated from Eq. (5).

$$\text{CPMA of } \text{A}_{\text{Case 4}} = \frac{Q_2^{AB} + Q_2^{AC} + Q_3^{ABC}}{P(A)} = 0.417 \qquad (5)$$

The assumption that all components are identical results in the same CPMA for component B and C. This result can be interpreted that the dependency of entire components is also about 0.417 because they are identical.

The next shows the case of which components are not identical. Let us modify the probability of failure in case 4 to have asymmetry among components. Suppose that the dependencies between A-B and A-C are same, but B-C has a half of dependency of A-B. Then 2 components failure probability in case 4 can be simply assumed as shown in Table IV.

Table IV: Failure probability of Q_2 assuming non-identical components

	Failure Probability	Remarks
$\mathbf{Q_2^{AB}, Q_2^{AC}}$	6.0E-03	
$\mathbf{Q_2^{BC}}$	3.0E-03	Half of AB or AC

Assuming the same conditions for case 4 except for 2 components failure probability, SDI and CPMA can be estimated using the minimal cut sets in Table I.

Table V: SDI and CPMA when components are non-identical

	SDI		CPMA
A-B-C	1.259	**A-B-C**	N/A
A-B	1.150	**A**	0.417
A-C	1.150	**B**	0.364
B-C	1.100	**C**	0.364

As can be seen in Table V, the dependency between B-C is weaker than A-B or A-C, therefore the SDI and CPMA related to B-C has slightly low values. Since CPMA is dedicated to a single component (or a single unit), it does not deal with the dependency of whole components (A-B-C) at one time.

On the other hand, the SDI takes into account the dependencies across components (A-B-C) and also between components (A-B, A-C and B-C). Thus, it can be flexibly utilized with a result of multi-unit PSA in terms of a site dependency and/or support the conventional dependency metrics.

4. Conclusions

In this paper, the SDI and CPMA as an index for representing dependencies across a site were compared. In order to facilitate understanding and calculation, the failure probability of components with CCFs were evaluated instead of a core damage probability. CPMA is a useful index to investigate a dependency of a particular unit and it is expected that the SDI is intuitive to understand the dependencies and convenient to evaluate the level of dependency across a site as a backup metric.

ACKNOWLEDGMENTS

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