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Exploring site risk for a Multi Unit SMR Site

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The need to adequately account of unit interactions when conducting safety analysis of nuclear reactors was highlighted by the Fukushima disaster of 2011. Traditional PRA techniques considered each unit in isolation, which can lead to underestimation of risk when units can impact the safety of other units in accident scenarios. The need to implement multi-unit PRA will increase when SMRs become commercially operative, as it is expected that reactor units per site will exceed what is common today. This study developed a method for scaling site risk as the number of units per site increases, with particular focus on SMRs. A number of input parameters were selected depending on the nature of the site under investigation; an algorithm then projects from an input risk of unit in an *m* unit site, to the site risk of an *n* unit site, where n>m. It was found that even in the least conservative risk estimates, the site risk far exceeded linearly scaled risk metrics used by traditional analysis techniques. In addition, positive unit interactions were modelled whereby units were able to provide support to other units in accident scenarios.

Keywords: multi-unit PRA, SMRs, PRA, PSA, risk metrics, nuclear industry.

1. Introduction

The Business Energy and Industrial Strategy (BEIS) department in UK is looking to implement SMRs in the early 2030s; many other countries have similar goals (UK Research and Innovation 2020). The IAEA defines SMRs as reactors which output under 300 MEe (International Atomic Energy Agency 2021). Having a lower power output, many units will need to be situated together to reach capacities comparable to standard reactors. The UK government estimates cost savings approaching 14% per reactor when co-siting 12 units, so there is ample incentive for multi-unit sites (Ernst & Young 2016). Understanding the risks associated with unit interactions will become an essential requirement for SMR site construction, so it is key that all countries with a nuclear interest begin to understand and develop MUPSA methodologies. The purpose of this study was to develop a methodology for examining the risk posed by an *n* unit site, where $n > 1$. Although validity of results may be improved if a specific unit number per site were chosen, generalising to *n* units provides the advantage of outputting site risk for any unit number, and allows general patterns in the way site risk evolves with *n* (among other assumptions) to be analysed. In addition, it is unclear how many SMR units will occupy a site, and this will likely vary depending on the site. A variable unit input enables results to be more applicable to SMR sites where reactor numbers could be large. The algorithm is designed such that Core Damage Frequency (CDF) values can be inputted for a single reactor. The CDF of unit is then extrapolated to estimate the site risk of an *n* unit site.

2. Multi-unit PSA

2.1. Unit interactions

The Seabrook study (Pickard, Lowe, and Garrick, Inc. 1983) was the first MUPSA to be carried out (i.e. it accounted for unit interactions). The site comprised two units, and despite minimal sharing of systems, the findings showed that accident sequences involving both units contributed significantly to the overall risk level of the site (International Atomic Energy Agency 2019). However formal investigation of multi-unit PSA lay largely dormant following Seabrook and was only brought into focus following Fukushima. At Fukushima Daichi, the single unit analysis severely limited preparedness and response to the Tonkotsu earthquake ; for instance, it is assumed in a PSA that a unit, experiencing a loss of offsite power, can recover through support from neighbouring units. Unfortunately, all neighbouring units experienced the same IE so were unable to provide support (Yang 2014).

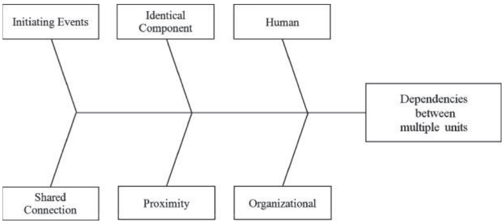


Figure 1 The different types of dependencies that exist between units on a site (Schroer and Modarres 2013)

Reactor units at the same site interact with one another. Much like the grouping of IEs, it is important to categorise the different types of interaction, enabling a sharper picture of multi-unit risk. Six types of dependencies through which units can interact have been identified (shown in Fig. 1) (Schroer and Modarres 2013). There are also degrees variation within each type of interaction. For example, a system may be shared between both units A and B equally; or the system may predominantly be used by unit A but has cross ties to unit B, so that B has access if required. The complexities of the interactions and the resulting propagation of uncertainties are the challenges of a robust MUPSA. The classification schema has been used to develop methodologies that combine the PSAs of single units on a site to arrive at a risk level for the site.

A key difference with multi and single unit PSAs is the definition of risk. Core damage frequency per reactor year provides a limited risk picture, being based on one reactor. An integrated risk for the site is required, which is termed site core damage frequency (SCDF). SCDF is defined as the probability of core damage to at least one reactor on site per site year (site year = time taken for combination of reactor operating time on site to reach one year) (Hassija 2014). However, arriving at a SCDF estimate is not simply a case of multiplying the single unit value by the number of units on the site. This would double count multi-unit hazards/IEs and would not account for other possibilities such as human response resources being diverted away from a damaged reactor due to an accident elsewhere on site.

$$CDF_A = \frac{(n-1)}{(r-1)!(n-r)!} \qquad (1)$$

$$SCDF = \frac{n!}{r!(n-r)!} \qquad (2)$$

Eq. 1 and 2 show the general expressions for deriving the coefficients for both CDF_A and SCDF for an n unit site, where r is the number of units interested by the event However, analysing the events impacting differing numbers of units is complex and resource intensive. As Son et al. (2019) indicate, we lack industry data pertaining to the frequency of initiating events affecting multiple units (Son 2019). Consequently, it is challenging to accurately separate out the number of different units impacted from hazards/IEs in a study such as this. A workaround is having a number of different input parameters, such as the probability for a SUI to propagate to another unit, which can be tweaked accordingly when data becomes more accessible.

3. MUPSA Methodologies and limitations

Many methodologies have been developed in recent years seeking solutions to fundamental questions of MUPSA, such as how core damage at one plant impacts the safety of neighbouring plants (Yang, Multi-unit risk assessment of nuclear power plants: Current status and issues 2018). As discussed, the classification schema was developed to augment single unit PSAs into a MUPSA. The classification of unit interactions was necessary so that different techniques could be developed to integrate the different types of interaction (Schroer and Modarres 2013). For example, interactions could be modelled by extending the fault trees of the single unit PSAs: others require parametric modelling, dealing with the conditional probability of a component failing given the failure of an identical component. The advantage here is that the site PSA does not have to start from scratch, saving time. It does run the risk however of reaching optimistic risk levels due to a shortcutting effect.

Other methods (Hassija 2014) propose constructing a MUPSA framework by considering the combinations of hazards and their resulting IEs impacting multiple units. It groups hazards into bins based on their severity. It then considers the number of different IEs that could be induced by a particular external hazard, and the total number of combinations by which this could play out between units. For example, it can be uncertain what type of IE a hazard can induce in a unit. It could induce one of a possible two types of IE per unit, so if we consider a 2-unit site, the number of ways in which core damage can occur simultaneously is 2x2 = 4. Each hazard type is sorted into bins based on their severity, and the combinations of induced IEs due to the hazard are used to determine a SCDF for that bin. The bins are then summed obtaining an overall SCDF value. Paper (Le Duy 2016) examines dependencies between units closely and differentiates between different shared system types. It seeks to develop an 'upgraded' risk model through inclusion of shared systems in the fault tree through consideration of a 2-unit site.

An implicit assumption in such studies is that the process of going from a two-unit site to an *n* unit site is identical. Paper (Kim 2018) indicates that approaches employed for two units may overestimate the risk when extending to *n* units. For instance, the way in which Common Cause Failure (CCF, failure of two or more components due to same underlying cause) is modelled for a two-unit site can lead to conservative risk values when applied to 3 units due to overestimation of all components failing. Care must be taken in extrapolating models from 2-units onwards, particularly when SMR sites could have units per site far exceeding conventional sites today.

To apply the methodologies discussed above, IE and hazard frequency data are needed, along with fault tree analysis to compute the corresponding CDF values. As SMRs are not currently commercially operative, this has not been possible; it would necessitate conducting a fully-fledged PSA of SMRs.

Instead, this study uses flexible input parameters that can be changed to fit the data, the specifics of which are discussed in the methodology section. These studies are useful in the context of this analysis in providing ways to model the dependency of units. For instance, paper (Hassija 2014) models dependency of components through proximity similarly to identical components. That is, if component A, near component B, has failed, the failure risk of B increases, much like CCF for identical components.

Despite the development of these methodologies and the continuing progress being made, there still exists several issues with MUPSA. Firstly, fault tree analysis becomes extremely complex as the number of units increases (the 'explosion problem') whereby possible sequence propagations through the fault tree become unwieldy, leading to ever expanding uncertainties (Seong 2018). Some methodologies attempt to overcome this using techniques combining single unit PSAs (Schroer and Modarres 2013); others look to reduce the number of possible sequences by grouping similar events together (Hassija 2014). Linked to the complexity issue is the lack of available data, arising due to the rarity of events and the uncertainties in the ways in which events can propagate to other units (Seong 2018).

Secondly, there is currently no universally agreed methodology for conducting MUPSA. It will only be possible for MUPSA to become common practice once one is established. The lack of guidance is evidenced by the Office of Nuclear Regulation (UK), who state:

"...there is also sometimes the need to consider the totality of risks from a site... for example when a single initiating event can affect multiple facilities." (UK Office for Nuclear Regulation 2014). The need to consider the risks posed by unit interactions is stated, but no guidance is given as to how licensees should demonstrate that they have assessed these risks.

4. Small Modular Reactors

IAEA defines small modular reactors as reactors generating less than 300MWe.

It is expected than in certain cases multiple SMR units will be sited together and they will likely share many structures, systems and components (SSCs); those that aren't shared will likely be identical. Although a disadvantage in terms of risks posed by CCFs, this dramatically reduces costs and improves efficiency. One of such system could be the turbine generator building. If the turbine hall was damaged, this, could impact multiple units. Further, there are several proposed designs generally fitting into four categories (advanced, innovative, converted and conventional). This complicates the situation regarding which SSCs will be shared. Some sources (Hidayatullah 2015) speculate that advanced SMRs could share secondary systems as well as essential equipment such as diesel generators. As it is unclear the extent of shared SSCs for SMRs, it was decided that dependency through SSCs be modelled through an increased probability of IE propagation from one unit to another for IEs that are likely to impact those SSCs.

5. Algorithm

The algorithm converts from the CDF value of a single unit on an *m* unit site to the SCDF (site

CDF) of an n unit site, where $n > m$. The input CDF is assumed to result from a full MUPSA analysis of the unit on the m unit site (i.e., it is assumed a MUPSA analysis is available for a specific unit on an m unit site with these values input into the program). This assumption is made because it is both not possible and impractical to carry out a MUPSA for SMRs. Therefore the purpose of the program is to project the risk posed to an n unit site based on the risk input from an m unit site.

As there are many variables involved in multi-unit methodologies (such as the different ways units can interact), it is necessary to impose some assumptions to reduce complexity. A list of assumptions used in developing the algorithm is given below.

- All units are identical.
- CDF is described by a normal distribution rather than a lognormal distribution for ease of calculations.
- All units are always at full power. Low power and shutdown modes are not considered
- One unit can only provide backup to one other unit even if it has the capability to back up more than one unit.
- The probability of independent IEs occurring simultaneously at two or more reactors is considered negligible.

The sections below summarise the different steps in the algorithm.

5.1. Grouping of Initiating Events (IE)

When considering multi-unit sites, it is possible to categorise initiating events considering their potential to impact multiple units. Hassija et al. (2014) groups initiators into a further three categories:

- Definite initiating events - always affect multiple units
- Conditional initiating events - can affect multiple units but only under certain conditions
- Independent initiating events - only impact a single units (Hassija 2014)

The first step in the development of the algorithm was to group initiating events based on whether they were independent, conditional or definite, and a CDF to each IE. Definite IEs were defined here as guaranteed to impact all units on site.

Following the grouping of IEs it the next step is to identify which reactors are affected by the IEs. The goal is to calculate the CDF resulting from a specific number of units impacted.

5.2. Modelling of unit dependencies

A further categorisation is needed, following the grouping of IEs based on units impacted: the grouping of CDF values based on the source of the interaction which creates the risk. Here, the source of interaction refers to the six ways units interact, presented in Fig. 1. For example, 10% of the CDF resulting from conditional IEs may be due to shared SSCs between units, and 15% to identical components. Although IEs are classed as ways units interact, they are common to all categories. In other words, the CDF from the category ‘identical components’ refers to the CDF resulting from an IE which impacted identical components, causing their failure. Similarly, the CDF resulting from human dependencies is due to an IE impacting multiple units, then limiting resources available to mitigate risk posed to any one unit (since resources are shared).

5.2.1. Propagation of IE due to proximity

An accident sequence started by an IE may propagate from the original unit to a neighbouring unit to their proximity. However, a unit can also recover from damage (this operationally means that the plant reaches safe cold shutdown conditions) and therefore they are no more part of the accident propagation. From a modelling perspective, the algorithm assumes for example that one unit has been impacted by an IE, and the IE has a certain probability p_d (chosen by the modeller) of propagating to other units. Therefore, each of the other units has a small chance of becoming affected. The next steps of the simulation model whether other units are affected by IE propagation (this is done by random sampling) and whether the damaged units have recovered. Note that the probability of becoming damaged of an intact reactor is impacted by the number of damaged units around it – for example if there are two damaged units and one intact, the probability of the intact unit becoming damaged is $1\text{-}(1\text{-}p_{d1})*(1\text{-}p_{d2})$. The algorithm terminates this sequence of modelling when no new unit is failed through random sampling.

5.2.2. Common cause failures

The probability of a component failure increases if an identical component has already failed because some manufacturing defect may exist in the component, or it may be unusually susceptible to the hazard initiating its failure (US Nuclear Regulatory Commission 2007). The modelling for intra-unit component failure is well-established. There is not an established model for failure of groups of components between units. It is thought to be over-conservative to apply intra-unit failure modelling to component failure between units. This is because a symmetric model is assumed for intra-unit components, meaning each component is truly identical and therefore has the same probability of failure. Asymmetry is introduced for inter-unit failure because one unit may have been recently refurbished for example, meaning components have different ages. Further, each unit has different component surveillance testing times, meaning component defects are identified and replaced at different times (Soga 2021). In the algorithm, similarly to system cross-ties, it is assumed that a unit has a total of m components and requires X functioning components to operate. It is assumed that an IE impacts all units and a percentage of those units fail due to failure of at least X components. No unit backup is assumed here as this model deals with components that do not have cross-ties to other units. The asymmetry is modelled by assuming each unit has a slightly different probability of component failure, which is generated at random within a probability range p_1 and p_2.

5.3. SCDF increase due to increasing unit number per site

After modelling each type of dependency, the CDF must be 'boosted' when going from an m to an n unit site, where $n > m$. Considering a two-unit site, the CDF from conditional IEs due to proximity may be 5×10^{-5} pry (per reactor year). This increases in to a 3-unit site, as the frequency of conditional IEs increases (due to there being an extra unit), as does the average number of reactors impacted from each conditional IE. The increase in CDF from 2 to 3 units will be the additional frequency of events multiplied by the average additional number of reactors impacted per IE. The latter figure is calculated by multiplying the probability of a particular number of units within a site becoming impacted by the number of units impacted itself, repeated for each combination of unit number and summed. A 3-unit site may, for example, see 60% of conditional IEs only impact 1 unit, 30% impact 2 units, and 10% impact all 3 units. The average number of units impacted per IE would then be $(1\times0.6) + (2\times0.3) + (3\times0.1) = 1.5$ units. The difference between this and the value for a 2-unit site is calculated and multiplied by the increase in frequency of events, giving a boosting factor to be applied to the input CDF.

6. Results

The results were obtained running the algorithm in Monte Carlo mode for 10,000 runs. The input table used for the simulation is presented in Table 1 below

Table 1 Input into the algorithm. High, medium and low SU CDF refer to the ratios of initial (input) CDF deriving from independent, conditional and definite IEs

A	SU CDF: High, CIE: 12%, CCF: 30%
B	SU CDF: High, CIE: 25%, CCF: 55%
C	SU CDF: High, CIE: 40%, CCF: 70%
D	SU CDF: Medium, CIE: 12%, CCF: 30%
E	SU CDF: Medium, CIE: 25%, CCF: 55%
F	SU CDF: Medium, CIE: 40%, CCF: 70%
G	SU CDF: Low, CIE: 12%, CCF: 30%
H	SU CDF: Low, CIE: 25%, CCF: 55%
I	SU CDF: Low, CIE: 40%, CCF: 70%

In Tab. 1, High, Medium and Low Single Unit (SU) CDF refer to the ratios of initial (input) CDF deriving from independent, conditional and definite IEs. The specific ratios are:

- High: 70% independent CDF, 20% definite, 10% conditional
- Medium: 65% independent, 20% definite, 15% conditional
- •Low: 55% independent, 25% definite, 20% conditional

The CIE value in the table is a measure of proximity – therefore the chance of a conditional IE spreading to the neighbouring units. These combinations of inputs are expressed by letters A to I. The first set of simulations were run assuming no sharing of systems (units cannot provide backup to other units)

The CCF modelling was increased alongside the percentage of conditional IEs as unit proximity increases the chance of a CCF event since a hazard is more likely to impact more units.

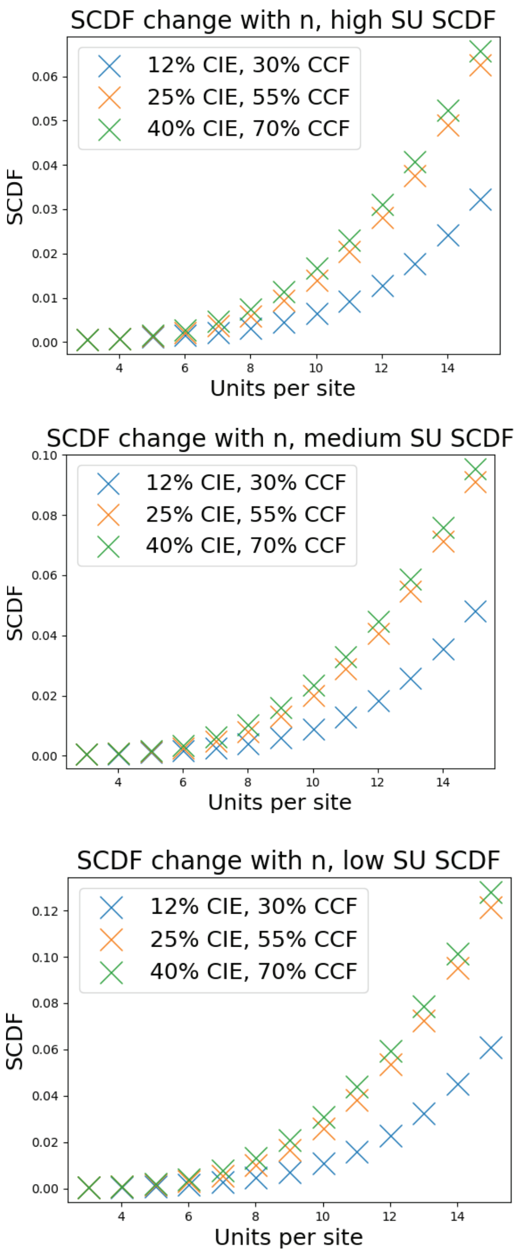
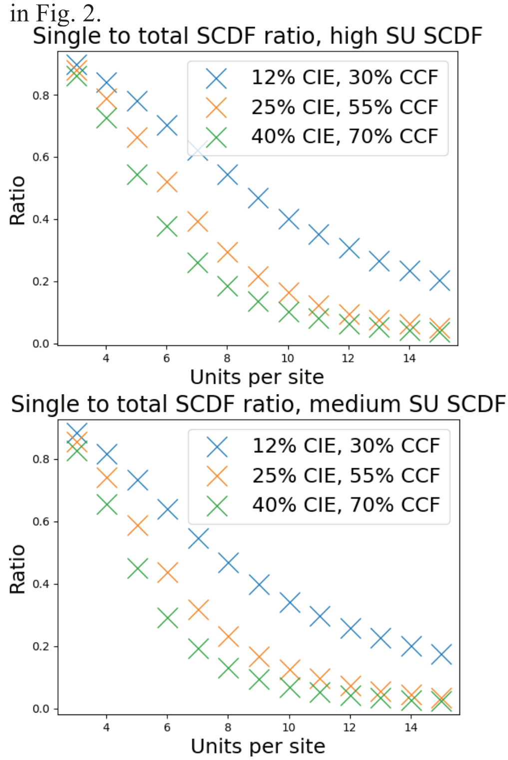


Figure 2 Plots showing how SCDF changes with unit number per site. Each graph shows 3 datasets where the probability of CCF failure and CIE propagation has been varied, but the ratios of input CDF arising from independent, dependent and conditional IEs have been held constant. The CDF ratios have then been varied for each graph, meaning there are a total of 9 combinations of input values.

An exponential relationship can be observed from the plots in Fig. 1. The exponential increase rate in the relationship is determined by the extent of the dependencies between units. A high percentage chance of conditional IE propagation (for example input C) represents a site where units are packed closely together, so a fire in one unit has an increased chance of spreading to another unit. It is expected that a site in which only negative unit interactions are considered should show higher rates of SCDF increase with increasing unit number per site – conditional IEs have an increased chance of impacting more units as unit number per site increases. In addition, a higher chance of conditional IEs propagating to other units results in a higher number of units becoming impacted, leading to a higher SCDF value.

The ratio of SCDF values resulting from the IEs only impacting single units (this includes conditional IEs which only impact single units) were calculated since they provide the conditional probability of a unit experiencing core damage given that another unit on the site has already experienced core damage. These ratios are shown in Fig. 2.



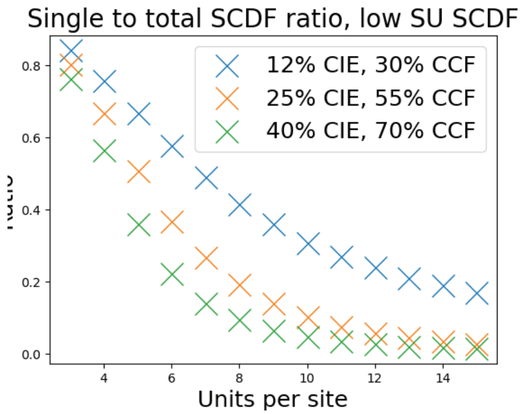


Figure 3 Plots showing the ratio of CDF impacting only single units to the total SCDF. In each graph CCFs and CIE propagation has been varied, but the ratios of input CDF arising from independent, dependent and conditional IEs are held constant.

When increasing the number of units n at a site, the major contribution to SDCF comes from conditional IEs. This is because as the number of units increases, the CDF due to independent IEs increases linearly with n and the CDF due to definite IEs also is assumed scaling with n Stutzke (2014), as there is only ever one way in which all reactors can be impacted.

Following from the above, the exponential increase observed in Fig. 2 must derive from the conditional IEs and specifically those that impact multiple units.

Given that CIEs are the source of the exponential relationship, it is important to better understand how they impact SCDF values. This is predominantly why the CDF ratios for CIEs, independent IEs and definite IEs have been varied and a partial section of the results is summarised in Table 2.

The first 3 rows (A, B and C) of Table 2 represent the case in which the CDF from CIE is lowest (10% of the total CDF). The CDF ratio is fixed for rows A, B and C, but the unit interaction probability has been varied (as laid out in Table 1). Looking at row *A*, if a linear relationship as to be assumed in which SCDF was simply n times the individual unit number, the SCDF for a 15-unit site would be the CDF of single unit, $2.3\text{x}10\text{-}^{04}$, times 15 obtaining $3.45\text{x}10\text{-}^{03}$ psy (sy = site year), whereas when unit interactions are considered, the SCDF is nearly 10 times bigger than $3.45\text{x}10\text{-}^{03}$ psy.

Table 2 SCDF data for unit number per site. The letters correspond to a specific set of assumptions

	Number of units					
***SCDF* (10^{-4})**	**3**	**5**	**9**	**13**	**14**	**15**
A	5.64	11.40	46.12	177.68	243.18	323.91
B	5.72	13.78	94.48	377.53	490.53	625.99
C	5.78	16.05	115.69	408.70	524.41	657.75
D	5.49	12.00	60.77	258.55	355.18	481.90
E	5.61	15.38	131.57	548.14	714.22	912.61
F	5.69	18.79	161.13	589.54	760.09	953.89
G	5.08	12.01	72.27	327.13	452.21	610.83
H	5.25	16.75	168.37	725.37	952.90	1215.67
I	5.36	21.39	211.44	787.53	1014.06	1279.95

In Table 2, values in row *A* represent the most conservative case for increase in risk due to both low interaction probability and low CIE ratio. In the most extreme case (*I*), the SCDF is around 15 times the value arrived at from traditional analysis. Comparing row *A* to *I*, the SCDF for 15 units is a factor of 4 larger but the average percentage probability of interaction of CIE and CCFs only increased by a factor of 2.8 (CIE double weighted as the CDF value for this was double that for CCFs). This difference therefore highlights the importance of accurately assessing the likelihood of conditional IEs impacting multiple reactors, since the values not only dwarf those estimated by traditional techniques, but also they do not scale linearly with unit interaction probability.

When examining rows *B* and *C* of Table 2, it can be observed that the difference between the *B* and *C* SCDF values for sites with more than 9 units remains relatively constant, and in fact begins to decrease for over 13 units. The trend for site with a low number of unit is generally that the rate of increase of SCDF is larger for higher interaction probabilities, although this is evidently not always true for larger n values. This can be explained by the fact that as n increases, the probability of a conditional IE impacting all units increases because conditional IE propagation becomes more likely. Additionally, the modelling assumes that if unit A impacts units B and C on a 10-unit site, the remaining operational units have a nearly double chance of becoming impacted since there are now two damaged reactors on site (unit A having recovered). With large n values, the probability of numerous reactors being impacted simultaneously increases, which therefore dramatically increases the chances of the remaining reactors becoming impacted. These factors combine to result in a much higher probability of all units becoming impacted. Therefore, although the higher probability of interaction between units assumed in row C of Table 2 results in an initially higher rate of change at low n, the conditional IEs begin to impact all of the reactors on site much more frequently as n increases, meaning that the exponential factor arising from combinations of units saturates, and IEs impacting all units begin to dominate.

7. Conclusions

The purpose of this study was to develop a method for estimating risk from a single unit on an m unit site to a site risk for an n unit site, where $n > m$. This was achieved through accounting for various unit dependencies, including common-cause failure, whilst also grouping risk based on the number of reactors an IE would impact following its occurrence. A number of input parameters can be varied in the algorithm, such as the ratio of CDF from conditional IEs to CDF from independent IEs; the probability of interaction between units; and the probability of component failure due to common-cause IEs. The output was SCDF for an n unit site, given an input CDF for one unit on an m unit site. An exponential relationship between SCDF and unit number was found, with the rate of change being determined by the extend of unit dependencies. Further, it was found the exponential nature was driven by conditional IEs which impact unit numbers between 1 and all units on the site. A boosting factor was applied to go from the m to n unit site, which was calculated via accounting for both the increased frequency of events along with the increased number of units impacted per event. A key finding was that, for a 15-unit site, the least conservative estimate of risk (limited unit dependencies) was still nearly 10x larger than the risk estimated if each reactor is assessed in isolation (how many PSAs are currently carried out). Further work not reported in this paper has modelled recovery of units due to shared connections.

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