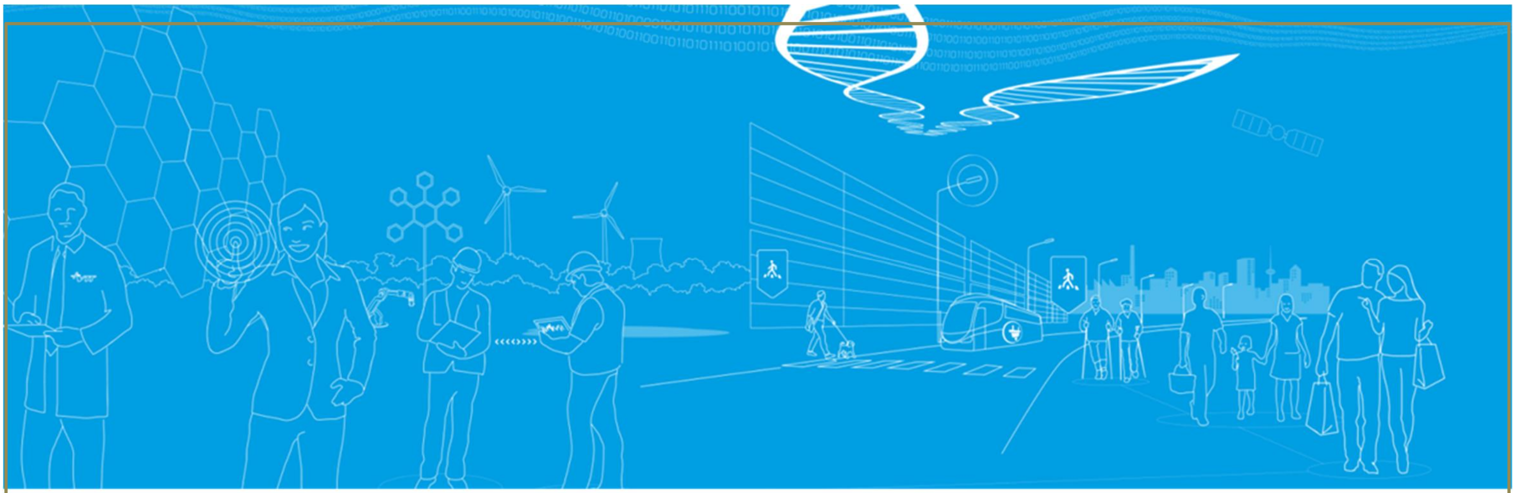

A methodology for preliminary probabilistic multi-unit risk assessment

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Summary

In this study, a methodology is outlined to estimate the importance of multi-unit accidents for a site with more than one reactor unit.

The suggested approach is based on:

- Identification of dependencies
- Qualitative and quantitative screening
- Estimation of frequencies/probabilities for screened in dependencies
- Calculation of the Multi-Unit Core Damage Frequency (MUCDF) or Multi-Unit Large Early Release Frequency (MULERF) using primarily conditional quantification of single unit models (together with the frequency/probability of the dependence)
- Sum of the MUCDF/MULERF for the identified dependencies to estimate the total MUCDF/MULERF

The approach is considered a conceptual approach, and there are a number of outstanding issues that could be studied further. Most importantly, the approach needs to be validated using full scope PRA models.

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1. Introduction

The Fukushima Daiichi accident in March 2011 pointed out that the risk of external events affecting multiple nuclear power plant (NPP) units is significant. Consequently, interest on multi-unit probabilistic risk assessment has also increased. A large part of the nuclear power sites houses more than one NPP and/or other nuclear facility such as a spent fuel pool storage.

Currently, multi-unit risks have not typically been adequately accounted for in risk assessments. Due to possible dependencies between the units at a site, the question of several simultaneous reactor accidents is not one of possibility but rather one of probability [1]. Based on the literature study [2] there is an increased interest to account for multi-unit issues. A large part of the research seems to focus on identifying and accounting for different kinds of dependencies and on external hazards.

In this study, the goal is to outline a rather simple methodology for preliminary probabilistic multi-unit risk assessment. The method should enable the identification of risks and deficiencies that can affect several units and assess their importance. The goal is that the method (especially the dependence identification part) can be used to support also other analyses than PRA.

Even though the method focuses on multi-unit sites, it is relevant also for a single unit site with several radioactive sources. The method should primarily not be considered as an approach to construct a full scope integrated MUPRA model. The objective is to get indicative results with limited resources. The aim is to compute risks related to different multi-unit events and dependencies and also to get an approximation of the total multi-unit risk. Based on the method it should also be possible to determine if some insignificant dependencies (or units e.g. used spent fuel pool storage) can be screened out from a full scope MUPRA or if it is at all worthwhile to perform a full scope multi-unit PRA based on the identified dependencies.

The idea is that the methodology utilizes existing PRA models and traditional PRA methods (event tree-fault tree approach) as much as possible. In some cases, alternative approaches can be considered. The focus of the method development is on level 1 PRA but in principle the method can also be applied to level 2 PRA.

The rest of this report is structured as follows: Section 2 presents and discusses different MUPRA risk metrics. In section 3, the needed initial data and supporting analyses are discussed. The MUPRA methodology is outlined in section 4. Sections 5 and 6 conclude this study. In Appendix A, a simplified application of the methodology is presented.

2. MUPRA risk metrics

The risk metrics used for single reactor PRAs are often core damage frequency (CDF) and large early release frequency (LERF). The formulation of relevant risk metrics and criteria for multi-unit PRAs has not yet solidified to specific industry standards. The reason for this is the fact that application of single reactor criteria to a multi-unit site is neither simple nor straightforward.

Risk metrics of single unit core damage frequency is straightforward for a site with one operating reactor. For a site with two operating reactors, there is a possibility that core damage could occur at unit 1, unit 2, or concurrently at both unit 1 and unit 2. In this case, the core damage frequency for unit 1 would be the sum of the independent core damage frequency and the frequency of simultaneous core damage. The frequency for a multi-unit accident would be the frequency for simultaneous core damage of both units. For a site with more than two reactors, there is still another level of complexity where multi-unit risk metrics can be defined by any combination of the sums of single-unit core damage frequency metrics, as demonstrated in Figure 2-1.

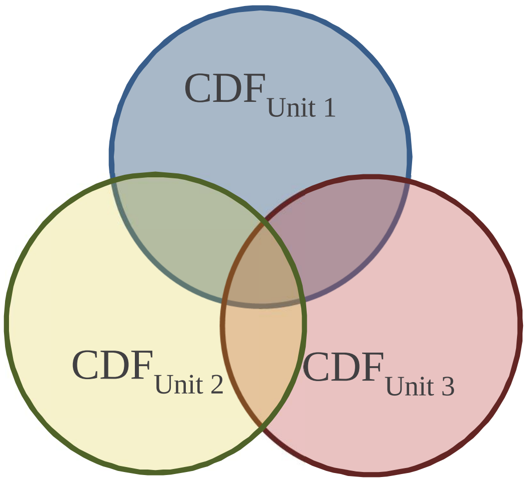

Figure 2-1. Multi-unit risk metrics can be defined by any combination of sums of single unit core damage frequency metrics.

The consideration for various permutations of single-unit CDF in MUPRA has given rise to the following multi-unit CDF metrics [3]:

- Single Unit Core Damage Frequency (SUCDF) – frequency of a reactor accident involving core damage on one and only one reactor unit per site-calendar-year.
- Multi-Unit Core Damage Frequency (MUCDF) – frequency of an accident involving core damage on two or more reactor units concurrently per site-calendar-year
- Site Core Damage Frequency (SCDF) – frequency of a reactor accident involving core damage on one or more reactor units concurrently per site-calendar-year.

It is important to clarify that SUCDF is not the same as a specific unit's CDF. CDF normally reflects the estimated frequency of core damage per reactor-calendar-year associated with a particular unit on the site. SUCDF is the sum of all CDFs involving single core damage. In Figure 2-2, SUCDF and MUCDF are separated in order to highlight the contributions to SCDF from single and multi-reactor accidents.

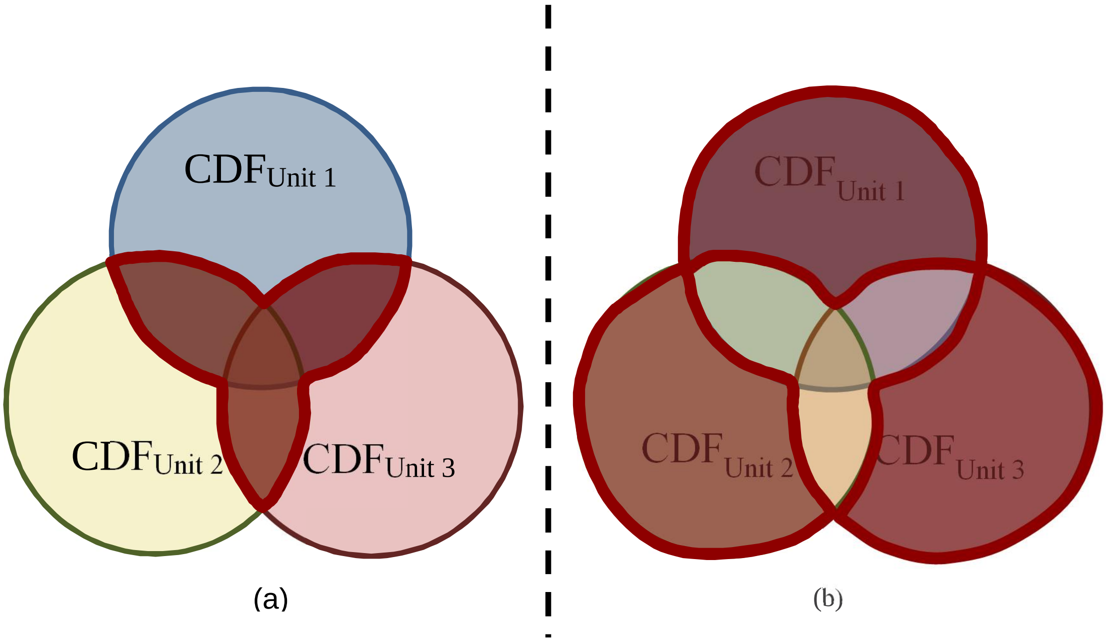

Figure 2-2. (a) The red shaded area represents multi-unit CDF (MUCDF). (b) Area representing single unit CDF (SUCDF).

The sum of the core damage frequencies from all contributions, measured on a frequency per site year basis, is the SCDF.

What is different regarding release metrics from a single unit PRA is the need to account for releases from multi-unit accidents. Similar considerations can be made for multi-unit release frequency metrics as were discussed for multi-unit CDF metrics. Release frequency metrics for multi-unit PRA could then be [3]:

- Site Large Early Release Frequency (SLERF) – frequency of a large early release from an accident involving <u>one or more reactor units</u> simultaneously per site-calendar-year.

- Site Release Category Frequency (SRCF) – the frequency per site-calendar-year of each distinct release category for a multi-unit level 2 PRA. These release categories include the release categories already defined in the single unit level 2 PRA for each unit, for releases from a single reactor unit, as well as categories for accidents involving multiple units.

The SLERF may involve single reactor accident sequences with releases from a single unit as well as releases from multiple reactor accidents that combine to meet these same criteria. For the large release there is hence no meaning in splitting up large releases from one or several reactor units, a large release is large irrespective of the number of sources. For a full scope level 2 MUPRA, the SRCF can be used.

In the methodology outlined in this document, MUCDF is used as the main risk metric for level 1. The reason for this is to keep the focus on multi-unit dependencies. In addition, the risk metric multi-unit large early release frequency (MULERF) has been used for level 2. The MULERF is just a part of the total large early release frequency from a site, but it is used here to capture dependencies that can lead to large early releases from more than one unit concurrently.

3. Initial data and supporting analyses

This chapter discusses initial data and supporting analyses needed for MUPRA in general level. The identified documents, materials and analyses are not specifically related to the MUPRA methodology outlined in the next chapter.

3.1 Existing documents and materials

PRA models of individual units are an important basis for MUPRA if they exist. MUPRA analysis likely uses partially same event trees, fault trees and data as PRAs for single units. One way to study important multi-unit scenarios is to examine **minimal cut sets** generated from the models of individual units in order to identify minimal cut sets that contain events that affect multiple units.

If PRA models of individual units do not exist, the situation is completely different. Then it is possible to take multi-unit dependencies into account in PRA right from the beginning, and the construction of a single PRA model for the whole site is an option. This report focuses on the case where the PRA models of individual units exist beforehand.

Initiating events for MUPRA can be identified based on **external hazard analyses** even though multi-unit effects may not have been considered in those analyses.

Dependencies between units can be identified based on **plant description, system descriptions and system analyses**, especially concerning safety and auxiliary systems. These dependencies can be shared systems, functional dependencies between systems, or identical or similar components between units. For shared systems, the prioritisation of the use needs to be clarified, i.e. which unit uses shared system first.

Human actions affecting multiple units can possibly be identified based on **human performance analyses**. Especially, maintenance team common to multiple units needs to be considered in MUPRA. Maintenance team's way of operation in multi-unit accidents needs to be found out. **Emergency instructions** can also reveal information relevant to MUPRA.

For MUPRA, it may be needed to consider if a fire or flood can spread from one unit to another. **Fire and flood analyses** can provide some information for that, but it is however likely that new multi-unit fire and flood analyses are needed.

3.2 New supporting analyses

The following new analyses may be needed so that proper MUPRA can be performed:

- External hazard analyses may need to be updated for MUPRA so that all initiating events that can affect multiple units can be identified and multi-unit effects can be modelled.

- MUPRA requires updated analyses for the success criteria of safety systems because longer time windows need to be considered when accidents occur in multiple units than when an accident occurs only in one unit. Updated success criteria can affect event trees, fault trees and data.

- Dependence and common cause failure analyses considering multiple units are needed for MUPRA.

- Human performance analyses considering multiple units may be needed so that human errors and maintenance operations can be modelled in MUPRA. Organization level analyses may also be needed.
- Analyses of new accident sequences are needed if new event trees are developed for MUPRA.
- It needs to be analysed how an accident or radioactive release in one unit affects the safety of other units.
- Potentially, there is a need to analyse if a fire or flood can spread from a unit to another and how probable it is.

4. MUPRA Methodology

This chapter outlines a methodology for straightforward and simplified MUPRA. The purpose is to produce indicative results with minimal work resources. The main goal is to analyse risks of different multi-unit events and dependencies in order to identify most important dependencies, but an approximation of total multi-unit risk is also calculated. The idea is to perform MUPRA utilising existing unit PRA models as much as possible. The methodology can be applied only if PRA models exist for individual units.

The methodology contains ten steps:

1. Identification and classification of multi-unit dependencies
2. Analysis of identified dependencies
3. Probability estimation
4. Extension of unit PRA models
5. Screening of events and event combinations
6. Computation of conditional accident probabilities
7. Computation of risk metrics of multi-unit event combinations
8. Construction of new multi-unit model
9. Computation with the new multi-unit model
10. Computation of multi-unit accident frequency and event importance

In steps 1-3, multi-unit dependencies are identified, analysed and modelled, and probabilities are estimated for them. Then multi-unit dependencies are analysed using existing PRA models of individual units in steps 4-7. If some dependencies cannot be analysed using single unit models, they are analysed using a new multi-unit model in steps 8-9. Finally, total results are calculated in step 10.

The steps indicated may need to be iterated, as identification, screening and probability estimation is an iterative process.

The analysis is performed for a set of NPP units and it considers case where an accident occurs in each of the units. If the site contains more than two units, the analysis can be performed for each unit combination separately or in parallel. Once performed for one combination, the analysis can easily be repeated for other combinations with much smaller resources.

4.1 Identification and classification of multi-unit dependencies

In this step, events relevant to MUPRA and dependencies between those events are identified. Presumably, some events appear in the PRA models of individual units whereas some do not. Any other multi-unit dependencies are also identified. The initial data and supporting analyses identified in section 3 functions as a basis for this step. Identification of dependencies does not require the PRA itself and it can provide important information for other analyses as well.

The identification process includes the classification of the dependencies. For the classification the six main categories identified in [4] can be used:

- Initiating events. There are two types of initiating events that can affect multiple units at a plant site; 1) initiating events that affect always multiple units, 2) initiating events that under certain circumstances affect multiple units. In addition, certain single unit events may also have the potential to propagate to other units on a site.
- Shared connections. This class refers to links that physically connect Systems, Structures, and Components (SSC) of multiple units. These SSCs can, for example, include electrical power supplies, emergency diesel generators or fire water systems.
- Identical components. Components that have the same design, operation, and operating environment in multiple units are prone to common cause failures.
- Proximity dependencies exist when a single environment has the potential to affect multiple units.
- Human dependencies exist when a human machine interaction affects multiple units.
- Organizational dependencies exist when an organization somehow connects multiple units, typically by some sort of logic error that spreads in the organization.

In the identification step, the cause and effect of the dependencies need also to be analysed. This information can be utilized, for example, in prioritising dependencies and in screening out dependencies with improbable causes and minor effects in the next step.

Each dependence category is discussed below. Human and organizational dependencies are a specific challenge when it comes to MUPRA. These dependence categories are briefly discussed, but no approach for assessment of human error probabilities is suggested in this preliminary probabilistic multi-unit assessment methodology.

4.1.1 Initiating events

The existing initiating event analyses performed for the existing single unit PRAs should be reviewed to identify which events can affect one unit only and which events can impact multiple units concurrently. The initiating events could be categorized as follows:

- Single Unit Events – the initiating event would occur in one unit only and would not affect other units tentatively (except possibly at a later phase of the accident), e.g. pipe break LOCA.

- Multi-Unit Events – the initiating event would clearly challenge two or more units or radiological sources on the site concurrently, e.g. seismic events.
- Partial Multi-Unit Events – the initiating event, as currently defined, could occur on a single unit, or impact multiple units, depending on the cause, e.g. loss of offsite power which could occur on a single unit or any combination of units. Events in this category would then be broken down and then placed into one of the previous initiating event categories.

It might be necessary to go back to a more comprehensive list of potential initiating events that was screened down to those included in the individual PRAs to see if any events screened out might be relevant to analyse in the multi-unit context.

Partial multi-unit events may, in the preliminary probabilistic multi-unit risk assessment, conservatively be considered as multi-unit events to avoid further analyses. Some loss of offsite power events can for example be caused by internal plant faults that may be confined to a single unit, while others are caused by switchyard faults that could impact any combination or all units on a site. To fully analyze the appropriate multi-unit combinations affected by each cause, more detailed analyses will most likely be necessary.

All initiating events, including events originating from internal or external hazards, can then be categorized based on their impact.

In a more comprehensive MUPRA, initiating events during other plant operating state than at-power also have to be considered, to cover for example initiating events that could occur in a shutdown unit and propagate to an operating unit.

On a site with more than two reactor units categories for initiating events impacting different combinations of two, three, etc. reactor units must be added.

4.1.2 Shared connections

There are different types of shared connections in a nuclear power plant. These connections can be categorized according to the approach used in [5], where the two main categories “structures and facilities” and “systems and equipment” are used, the latter having three sub-categories:

- Sharing of structures and facilities

  Examples of shared structures and facilities include for example service water intake structures and different types of storage tanks. There are also plant designs where for example turbine and/or auxiliary buildings are shared.

- Sharing of systems and equipment
  - Systems that can support several units simultaneously

    Systems in this sub-category include for example station blackout gas turbines and common fire protection systems.

  - Independent systems at each unit that can be cross-connected to support another unit or single systems able to fully support only one single unit at a time

Systems in this sub-category could for example include demineralized water distribution. Emergency diesel generators may also be configured to support only one unit at a time.

- Independent systems at each unit sharing standby or spare equipment

  Systems in this sub-category include for example portable pumps for independent cooling.

Which connections that are shared differ widely between plants, even between plants with the same vendor. Many of the shared connections are however not important from a PRA point of view, e.g. shared office buildings and shared communication systems.

If any shared system is only able to support one unit at a time, this system shall only be accounted for in one unit.

4.1.3 Identical components

This dependence category refers to common cause failures (CCF) of identical systems or components at several units due to causes other than external hazards (e.g. design errors or maintenance errors repeated on several units). In [4] strong evidence is presented that dependent failures occur with a relatively high frequency involving multiple units.

It is very site specific which component types could be sensitive to inter-unit CCF. On a site with two reactor units of the same design the number of identical systems or components is of course larger than if the reactor units are of different design.

Available service data should be used to identify if some observed CCF involve failures on multiple units. For component types where inter-system CCF has been found negligible in the single unit PRAs, it is considered applicable to exclude inter-unit CCF for the same reason.

Generally, heavy components in cooling and electrical system such as emergency diesel generators and service water pumps should be included. If systems possible to cross-connect between units have been identified in the shared connections step, CCF should also be assessed.

4.1.4 Proximity dependencies

Proximity dependencies may be of importance in a MUPRA in two principal ways:

- An initiating event in one unit has the potential to spread to at least one other unit

  For units sharing structures and facilities or being closely located, internal hazards, such as an internal fire, can affect or spread to a neighbouring unit. Events of importance in this sub-category are typically identified in the initiating event step (see section 4.1.1).

- An accident sequence in one unit has the potential to affect at least one other unit

  Even if the initiating event is considered a single unit event there is possibility that a potential accident sequence could affect another unit. A severe accident induced hydrogen explosion may for example damage the structure of a neighbouring unit or throw material on the switchyard inducing another initiating event.

4.1.5 Human and organizational dependencies

Human and organizational dependencies are closely related, the difference between them lies in the root cause of the failure. Many of these dependencies could to be covered in the human reliability analysis (HRA) or the CCF analysis (e.g. maintenance errors), while some other dependencies are difficult to capture in a PRA (e.g. using incorrect vendor guidance).

Challenges include that a radioactive release from one unit in case of a multi-unit accident might affect critical operator actions that have to take place outside the main control room of another unit.

During a severe accident decision making command control shifts also from the control room to the emergency response organization. In the case of a multi-unit accident a single emergency response organization is responsible for coordinating the accident response for multiple units in differing accident phases. If the units share equipment, fixed or portable, the emergency response organization also has to prioritize the use.

4.2 Analysis of identified dependencies

Preliminary analysis on the importances of the identified multi-unit dependencies is performed qualitatively. The dependencies are ranked qualitatively in categories 'very important', 'important', 'less important' and 'insignificant' to:

- Ensure that the dependencies that are considered likely to be relevant are captured correctly in the quantitative analysis
- Screen out dependencies that do not require further analysis

The categories can be defined as follows:

- 'Very important' – dependencies where no additional SSCs are available to cope with an initiating event, e.g. a shared water intake
- 'Important' – dependencies where a limited number of additional SSCs are available to cope with an initiating event, e.g. diesel generators at a site with a station blackout gas turbine system
- 'Less important' – dependencies where a number of additional SSCs are available to cope with an initiating event, e.g. a shared fire water system
- 'Insignificant' – dependencies without effect on the risk for core damage or a radioactive release, e.g. a shared domestic water system

If a dependence is ranked as 'very important' or 'important' in the qualitative analysis this is expected to also be important from a quantitative aspect. If this is not the case, the quantitative analysis should be revisited to ensure that it properly accounts for the dependence. The qualitative importance analysis is hence a support to the quantitative analysis.

A quantitative screening process could be applied to reduce the amount of potential dependencies to be considered in the multi-unit model. A suggested approach to quantitatively identify which dependencies that are relevant for a more detailed analysis (not covering initiating event as these are treated separately) is presented in the following.

Perform the following steps for each unit:

1. Generate a total CDF cut set list for unit x.

2. For identified dependencies, select appropriate basic event(s) to represent each dependence respectively. If no suitable basic event(s) exist, the dependence is not screened out at this point. The basic event(s) to model the dependence can be added to the model in step 4 (see section 4.4), and another screening procedure is performed in step 5 (see section 4.5).

3. Calculate the maximum contribution to the multi-unit core damage frequency (MUCDF) from unit x for each relevant dependence i according to:

$$MUCDF_{i,ux} = FV_{i,ux} \times CDF_{ux}$$

   where:

   $FV_{i,ux}$ is the Fussell-Vesely importance for dependence i in unit x, and

   CDF_{ux} is the total core damage frequency for unit x.

4. If $MUCDF_{i,ux}$ < 1E-08/rx-yr, screen out the dependence.

Include all dependencies with $MUCDF_{i,ux} \geq$ 1E-08/year for each unit in further analyses.

The screening criteria 1E-08/year is a suggestion and if deemed necessary a more stringent screening criterion can be applied. The reason for 1E-08/year is that the safety goal typically applied for large early release frequency (LERF) in a single unit PRA is 1E-07/year. If the contribution to the MUCDF is less than 1E-08/year for any of the units, the contribution to a multi-unit release is expected to be insignificant.

After the first dependence screening process important initiating events should be selected. This process is depicted in Figure 4-1.

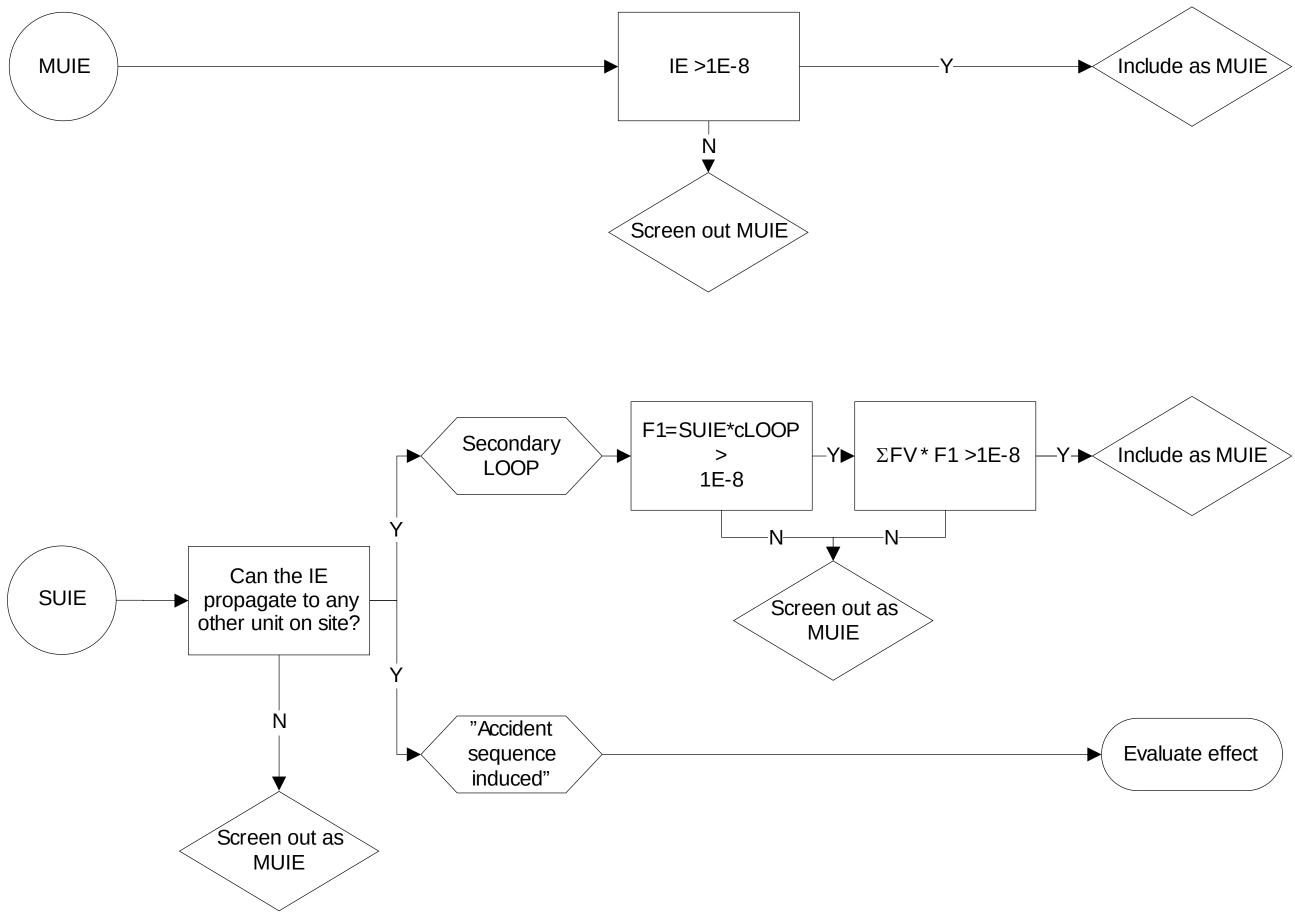

Figure 4-1. Selection of important initiating events in the preliminary probabilistic multi-unit assessment.

All multi-unit initiators (MUIE) are relevant for further analysis, if their frequency is greater than 1E-8/year. Single-unit initiators (SUIE) that cannot propagate to another unit can be screened out directly as MUIEs. If the initiating event can cause a secondary loss of offsite power, this can be evaluated using the Fussell-Vesely (FV) for the event representing the conditional loop (induced loop). If the F1=SUIE*cLOOP (cLOOP is representing the conditional probability for loss of offsite power and SUIE is the initiating event frequency) is less than 1E-8/year then it needs not to be considered further as MUIE. In case the conditional loop has relevance, it is only relevant to consider from a MUIE perspective if the dependencies caused by the shared systems/structures have some significance. This is evaluated in the step where the frequency is evaluated for the sum of all potential relevant dependencies (calculated as FV for all relevant dependencies) are considered, in a situation where the initiating event has caused induced loop.

Initiating events in one unit induced by an accident sequence in another unit have to be evaluated separately. These sequences are in most cases expected to be possible to screen out. Certain shared connections, such as linked reactor building ventilation systems making it possible for hydrogen to spread between units, can however increase the risk for such events. This part requires more research. At this point, no screening criterion is proposed.

If the identified sequences from PRA level 1, which are the sequences that are continued in PRA level 2, are of sufficiently low frequency – then the screening ensures that the dependencies relevant for PRA level 1 sequences that are to be continued to PRA level 2 are taken into account. In the PRA level 2 evaluation no additional combinations that are relevant to consider within PRA level 1 is expected to be identified. However, within PRA level 2 there can be additional dependencies to be considered (for example SAMGs and other operator actions).

4.3 Probability estimation

4.3.1 Parameters for individual events

All probability parameters of multi-unit events are estimated including:

- Probabilities and frequencies of events
- Conditional probabilities of dependencies, e.g. probability that an event affects multiple units
- Common cause failure parameters

For the estimation of probability parameters, the methods identified in e.g. [4] can be utilised.

4.3.2 Event combinations

The analysis will be performed for each relevant multi-unit event combination. Therefore, all possible combinations of the included multi-unit events are formed. In the following, also single multi-unit events are counted as multi-unit event combinations, i.e. combinations with only one event. Hence, an event combination can consist of either

- a multi-unit initiator,
- a multi-unit basic event (representing dependency or CCF),
- a multi-unit initiator and one or more multi-unit basic events, or
- multiple multi-unit basic events (without initiator).

For each event combination containing multiple multi-unit basic events without initiator, the frequency and repair time have to be estimated.

4.4 Extension of unit PRA models

If a multi-unit event is not found in the PRA models of individual units, it should be considered if it should be included because all risk important events need to be modelled in PRA. If a decision is made not to include an event, it should be considered if the PRA models contain an event (or group of events) that could act as a surrogate event (or group of events), i.e. an event with similar consequences. Chosen surrogate events need to be written down because they are used in step 6 (see section 4.6). Those events that do not appear in the models and do not have surrogate events have to be considered in step 8 (see section 4.8).

PRA models could also be modified otherwise. For example, success criteria and mission times could be updated if seen appropriate. It could be beneficial to make special versions of the models for this analysis so that original models remain untouched.

It shall be observed that a shared system, which is only able to support one unit at a time, shall only be credited for one of the units. For the other reactor units at the site, it should be considered unavailable. This is a simplification that leads to slightly conservative results, but removes the possibility for optimistic estimates.

4.5 Screening of events and event combinations

At this point, screening of multi-unit events and event combinations can be performed to reduce the number of computation cases.

1. Multi-unit events that were not screened out in step 2 (see section 4.2) can now be evaluated using estimated probabilities and frequencies (in step 3 section 4.3). Multi-unit events with sufficiently small probabilities can be screened out from further analysis. Also, the screening procedure of step 2 can be repeated for those multi-unit events that were not explicitly modelled in the PRA models of individual units before the extension of the models in step 4 (see section 4.4). All event combinations containing any event that is screened out have to be removed from the set of event combinations.

2. Using the probabilities/frequencies estimated in step 3, multi-unit event combinations below the selected screening criteria can be screened out. This could be performed through an event tree quantification, see example in section 4.7.

Following this step, all relevant dependencies that shall be included in the analysis are defined. The analysis will be performed for each multi-unit event combination (containing one or more events) that has not been screened out.

4.6 Computation of conditional accident probabilities

For each multi-unit event combination identified previously, conditional accident probability is calculated in each unit using the PRA model of the unit. Conditional accident probability can be either conditional core damage probability (CCDP) or conditional large early release probability (CLERP).

For an event combination containing multi-unit initiator (MUIE) the computation can, for example, be performed by setting the frequency of the initiator to 1 and the probabilities of other events in the combination to 1 (True), and calculating the total probability (as the frequency of the initiator is set to 1, the result calculated is in fact a frequency, but logically it is representing a probability).

Dependencies that are relevant to study and that are relating to the risk of simultaneous single unit initiators (SUIE) have to be treated separately. For these dependencies, conditional core damage frequency (CCDF) or conditional large early release frequency (CLERF) is calculated first. These can be calculated by setting the relevant event probabilities to 1 and then calculating the CCDF/CLERF for all the initiating events that are not representing MUIE. CCDF/CLERF value is not comparable to CCDP/CLERP values, and the formulas in the next section require conditional probabilities. Therefore, CCDF/CLERF value needs to be transformed into CCDP/CLERP. The transformation can be performed with the following formulas:

$$CCDP = 1 - e^{-CCDF \times t},$$

$$CLERP = 1 - e^{-CLERF \times t},$$

where t is the time the event is in effect, e.g. repair time. The CCDP/CLERP value is the probability that the accident occurs during t hours given that the event is in effect those t hours. If the analysed event combination contains more than one event, the repair time of the event combination needs to be estimated.

Surrogate events are used for events that do not appear in the models if possible. If unit models can be assumed to be sufficiently similar, it can be enough to calculate the CCDP/CLERP only in one unit to avoid computation with multiple PRA models.

4.7 Computation of risk metrics of multi-unit event combinations

The multi-unit core damage frequency or large early release frequency related to each multi-unit event combination is calculated. If the combination contains multi-unit initiator IE and multi-unit basic events BE_1, BE_2,…, BE_M, where M is the number of basic events, the corresponding multi-unit core damage frequency is

$$MUCDF(IE, BE_1, BE_2, \ldots, BE_M) = f_{IE} \cdot p_{BE_1} \cdot p_{BE_2} \cdot \ldots \cdot p_{BE_M} \cdot \prod_{i=1}^{n} CCDP_i(IE, BE_1, BE_2, \ldots, BE_M),$$

where f_{IE} is the initiating event frequency, p_{BE_K} is the probability of K:th basic event BE_K, n is the number of units considered, and $CCDP_i(IE, BE_1, BE_2, \ldots, BE_M)$ is the CCDP of the event combination calculated in the previous step of the methodology. If unit models are considered near similar, it may be sufficient to use approximation, e.g.

$$MUCDF(IE, BE_1, BE_2, \ldots, BE_M) = f_{IE} \cdot p_{BE_1} \cdot p_{BE_2} \cdot \ldots \cdot p_{BE_M} \cdot CCDP_1(IE, BE_1, BE_2, \ldots, BE_M)^n,$$

so that CCDP needs to be calculated only from one unit.

Notice that these formulas consider accident only in one specific combination of units, and this MUCDF is related to this one combination of units instead of all possible combinations. These calculations have to be performed for each combination of units on the site. As stated in the beginning of the chapter, the analysis is performed for one combination of units at a time. In the end, the results of different unit combinations can be combined to calculate total MUCDF of the site.

If the analysed event combination contains only multi-unit basic events BE_1, BE_2,…, BE_M (which means that the case of simultaneous single unit initiators is analysed), the corresponding multi-unit core damage frequency is

$$MUCDF(BE_1, BE_2, \ldots, BE_M) = f_{BE_1, BE_2, \ldots, BE_M} \cdot \prod_{i=1}^{n} CCDP_i(BE_1, BE_2, \ldots, BE_M),$$

where $f_{BE_1, BE_2, \ldots, BE_M}$ is the frequency of the combination of basic events $BE_1 - BE_M$.

Large early release frequencies related to multi-unit event combinations can be calculated similarly based on CLERP values.

If it is not possible to calculate the multi-unit risk of some event combinations using single unit models, it may be necessary to create an integrated model for the corresponding initiators. If such model is needed, it is outlined in section 4.8.

An example on the analysis of a MUIE is presented in the following. Event tree presented in Figure 4-2 is used to represent different computation cases related to “loss of offsite power” (LOSP) initiating event. Loss of offsite power can occur in combination with emergency diesel generator (EDG) multi-unit CCF or with service water system (SWS) multi-unit CCF or with both as well as without any other multi-unit events. The event tree approach does not necessarily have to be used. It is just one way to structure the analysis.

Loss of offsite power	Emergency diesel multi-unit CCF	Service water system multi-unit CCF				
LOSP	EDG CCF	SW CCF	No.	Freq.	Conseq.	Code
			1		EDG-I_SW-I	
			2		EDG-I_SW-C	SW CCF
			3		EDG-C_SW-I	EDG CCF
			4		EDG-C_SW-C	EDG CCF-SW CCF

Figure 4-2. Event tree representing multi-unit event combinations that contain loss of offsite power initiating event.

Following the formulas presented above, the following multi-unit CDF frequencies can be calculated:

$$MUCDF - Sequence1 = f_{LOSP} \times (1 - p_{EDG-CCF}) \times (1 - p_{SW-CCF}) \times CCDP_1(LOSP) \times CCDP_2(LOSP)$$

$$MUCDF - Sequence2 = f_{LOSP} \times (1 - p_{EDG-CCF}) \times p_{SW-CCF} \times CCDP_1(LOSP, SW - CCF) \times CCDP_2(LOSP, SW - CCF)$$

$$MUCDF - Sequence3 = f_{LOSP} \times p_{EDG-CCF} \times (1 - p_{SW-CCF}) \times CCDP_1(LOSP, EDG - CCF) \times CCDP_2(LOSP, EDG - CCF)$$

$$MUCDF - Sequence4 = f_{LOSP} \times p_{EDG-CCF} \times p_{SW-CCF} \times CCDP_1(LOSP, SW - CCF, EDG - CCF) \times CCDP_2(LOSP, SW - CCF, EDG - CCF)$$

4.8 Construction of new multi-unit model

A new multi-unit PRA model is constructed only for the analysis of those event combinations that could not be analysed properly using the PRA models of individual units.

4.9 Computation with the new multi-unit model

If new multi-unit model had to be created, see section 4.8, calculation of the risk metrics using this model shall be performed. The multi-unit core damage frequencies or large early release frequencies related to the event combinations in the multi-unit model are calculated. After this step, there are risk values available for all multi-unit event combinations.

4.10 Computation of multi-unit accident frequency and event importance

The core damage frequencies or large early release frequencies related to all multi-unit event combinations (from steps 7 and 9 see section 4.7 and 4.9) are summed up to calculate an approximate multi-unit core damage frequency or large early release frequency. This number indicates the magnitude of the multi-unit risk related to the analysed combination of units. Also, after the analysis has been performed for all unit combinations containing at least two units, total MUCDF for the NPP site can be calculated.

To calculate risk importance value, the multi-unit core damage frequency related to an event can be approximated by the sum of the calculated $MUCDF$ values:

$$MUCDF(E) = MUCDF(C_1(E)) + MUCDF(C_2(E)) + \cdots + MUCDF\big(C_n(E)\big),$$

where $C_1(E)$, $C_2(E)$,…, $C_n(E)$ are event combinations that contain event E. Both contributions coming from step 7 and step 9 should be included in this sum if applicable. Fussell-Vesely value of the event can then be calculated by scaling the MUCDF(E) value by the total multi-unit core damage frequency. Similar computation can be performed with regard to large early release frequency.

5. Discussion

The risks of a nuclear power plant site have not been analysed much as a whole. Instead, PRA has mostly focused on individual units separately. Therefore, there are no established methods to perform MUPRA. A methodology for simplified preliminary MUPRA has been outlined in this report. The validity of a new methodology can be judged best by real life application. When the methodology is applied to a real case, it is possible that some parts of the analysis need to be changed and the methodology evolves a bit.

Some parts of the methodology are outlined on quite general level. For example, methods to model multi-unit dependencies and estimate probabilities for events need to be developed in further studies. Also, some methods that are proposed are only tentative suggestions that can later be replaced by better solutions if needed.

In the method development, at least the following issues should also be considered and further studied:

- Risk metrics
- Mission time for the analysis
- The impact of plant operating states
- The impact of radioactive releases from one plant on the safety of an adjacent plant, (e.g., ground releases from one plant can hinder manual operations on the other plant)
- Structured approach for identification and classification of dependencies, especially HRA
- Modelling of shared systems
- Inter-unit CCF estimation
- Consequences of concurrent core melt accidents (e.g. the potential for two or more small releases that together form a large release because of an increased total source term)

- Alternative computation and modelling approaches (e.g. dynamic calculation to complement the traditional PRA modelling methods in some specific cases)

In the outlined methodology, MUCDF is used as the main risk metric for level 1. The SCDF, on the other hand, may be more suitable when the total risk of a nuclear power plant site needs to be calculated. It is possible to apply this methodology using the SCDF (by changing certain computation formulas), but then the analysis of single unit accidents needs to be included also. To quantify MULERF and SLERF the methodology has to be developed further. The consequences of concurrent core melt accidents in several units then have to be estimated. Since the accident progression may differ in different units even though the initiating event is common, a simplified approach should be found to minimize the number of plant damage states and release categories.

In single unit PRAs, the mission for the analysis is generally 24h. However, in MUPRA the mission time may need to be extended. From a level 3 perspective it is certainly needed to take a longer release time into consideration, but it is not evident how a prolonged mission time shall be applied in the calculation of MUCDF. It can be noticed that shared resources may be needed to be accounted for after 24 hours – but this is not only a MUPRA problem.

During different plant operating states, the risk profile for a plant can change. In addition, the available safety systems and recovery actions can differ. Thus, the methodology should also consider that the plants can be at different plant operating states during the same time period.

Also treatment of severe accident phenomena and the effects of radioactive releases should be considered. For example, ground releases from one plant can hinder repair/manual operations on the other plant(s). In addition, the fire brigade may not move in the area due to a release. In addition, a hydrogen explosion in one unit can cause damage to other units. Level 2 dependencies are likely more complicated to model than level 1 dependencies.

Since step 'Identification and classification of multi-unit dependencies' (see section 4.1) is quite important for the MUPRA methodology, it could be useful to develop a formal method to support the step. Such a method would also benefit other analyses that require information of multi-unit dependencies as an input.

Modelling of shared systems that can support only one unit at a time is one area that requires more research. In this report, it was suggested that a shared system is set failed in all units except one. This is a simplified and conservative way to perform the modelling. More accurate approach would select the supported unit based on accident sequences. It could be complicated to do that in this framework. If minimal cut sets were solved for multi-unit accidents, it could be easier to take shared system into account by manipulating basic event probabilities in minimal cut sets.

It would be possible to take some other type of approach to the computation as well. One possibility would be to solve minimal cut sets for a multi-unit accident by combining minimal cut sets of individual units so that multi-unit dependencies would be taken into account [6]. This approach could also be relatively simple, but it would require development of advanced software support.

An objective with presented methodology was that it should utilize existing PRA models and traditional PRA methods as much as possible. However, for modelling dynamic scenarios, e.g. one unit supplies power to another unit, the fault tree approach may not suit very well in all cases. In such cases, alternative more dynamic approaches, for example dynamic flowgraph methodology (DFM) [7] could be used. Different ways to utilize DFM as a part of PRA were studied in [8]. Dynamic methods could be useful also for quantification. It could be beneficial to further research the need and applicability of the alternative approaches in MUPRA context.

6. Conclusions

The methodology in this document can be used to estimate the importance of multi-unit accidents for a site with more than one reactor unit.

The suggested approach is based on:

- Identification of dependencies
- Qualitative and quantitative screening
- Estimation of frequencies/probabilities for screened in dependencies
- Calculation of the MUCDF/MULERF using primarily conditional quantification of single unit models (together with the frequency/probability of the dependence)
- Sum of the MUCDF/MULERF for the identified dependencies to estimate the total MUCDF/MULERF

The approach is considered a conceptual approach, and there are a number of outstanding issues that could be studied further. Most importantly, the approach needs to be validated using full scope PRA models.

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Appendix A – Simplified example of a preliminary probabilistic multi-unit risk assessment

The following small example illustrates how the preliminary probabilistic multi-unit risk assessment methodology could be applied practically. The example uses parts of the example PRA model EXPSA that comes with the RiskSpectrum® PSA installation. It is assumed that there are two units at the site analysed and that they their PRA models, represented by EXPSA, are identical. It should be noted that EXPSA is a simplified example PRA model and that it is being used with existing assumptions.

Since a simplified example PRA model is used and the main goal is to illustrate the work procedure and not numerical results, the example is limited to level 1 (MUCDF).

Step 1 – Identification and classification of multi-unit dependencies

Initiating events

The single-unit PRAs include three different initiating events that are considered in this example – large loss of coolant accident, loss of main feedwater and loss of offsite power. Table A-1 summarizes the categorization of these initiating events.

Table A-1 – Multi-unit initiating events categorization for the example site with two units

Category	Initiating event	Comment
A. Initiating events impacting both units at a site (Multi-unit initiating events – MUIE)	• Loss of offsite power (LOOP)	Both reactor units get power supply from the 400 kV offsite grid and share a common switchyard.
B. Initiating events impacting each unit independently (Single unit initiating events – SUIE)	• Large loss of coolant accident (ALOCA) • Loss of main feedwater (LMFW)	-

Loss of offsite power (LOOP) is typically a partial multi-unit event, where some events may be confined to a single unit only. To avoid further analyses, the conservative assumption is made that all LOOPs will affect both units. The initiating event frequency for a multi-unit loss of offsite power is therefore set to 1.0E-1/year.

Shared connections

The assumed shared connection between the two units are listed in Table A-2.

Table A-2 – Assumed shared connections between the two units

Shared connections	Description
Shared structures and facilities	
Office and service building	The office and service buildings for plant management personnel are shared by the units.
Shared systems and equipment	
Offsite power system	The offsite power grid is the preferred power supply for both units.
Gas turbine generation system	The gas turbine system is shared between the two units. The system provides electrical power of sufficient capacity to operate the main feedwater system (MFW) in one of the units for a period of 24 hours. It may also provide electrical power to manoeuvre valves in the residual heat removal system (RHR) in order to establish feed and bleed.
Fire protection system	The fire protection water supply system is shared by both units (but this is not included in this example).

Identical components

Components identical in both units are listed in Table A-3. It is also evaluated whether CCF is relevant to consider or not. For simplicity, a limited number of identical components is assumed. Pumps in other systems than the service water system are for example assumed to be different in the two units.

Table A-3 – Assumed identical components between the two units

System	Component	CCF candidate
AC power system (ACP)	• Diesel generators	Yes – same manufacturer, same environment, common maintenance team
Emergency core cooling system (ECC)	• Motor-operated valves (identical to EFW valves)	No – inter-system CCF (ECC/EFW) screened out in single unit PRA
Emergency feedwater system (EFW)	• Motor-operated valves (identical to ECC valves)	No – inter-system CCF (ECC/EFW) screened out in single unit PRA
Service water system (SWS)	• Service water pumps	Yes – same manufacturer, same environment, common maintenance team

Proximity dependencies

No initiating events that could spread from one unit to the other have been identified in step 1.

In this small example, that is limited to level 1, it has not been evaluated if an accident sequence in one unit has the potential to affect the other unit.

Human and organizational dependencies

No identification and classification of human and organizational dependencies have been performed. It is however assumed that the maintenance team is common to the two units, which has been taken into account when identifying CCF candidates.

Step 2 – Analysis of identified dependencies

The dependencies identified in step 1 are ranked qualitatively and assigned one of the four importance categories, see Table A-4.

Table A-4 – Qualitative analysis of dependencies

Identified dependencies	Qualitative importance ranking	Comment
Shared structures and facilities		
Office and service building	Insignificant	No effect on the risk for core damage or radioactive release. Not included in PRA.
Shared systems and equipment		
Offsite power system and switchyard	Very important	Ordinary power supply. A failure may result in a multi-unit initiating event (MU-LOOP).
Gas turbine system	Important	AC power back-up for MFW. Diesel-backed emergency feedwater and core cooling systems also available. Also AC back-up power for establishing feed and bleed with RHR.
Fire protection system	Less important	Not included in this example, but is expected to be ‘less important’ due to the fact that it is not affecting all rooms, and all systems are not made unavailable at a fire.
Identical components		
Diesel generators	Very important	The only AC power back-up system for safety related systems.
Service water pumps	Very important	The only primary cooling system for safety-related components.
Proximity dependencies		
-	*No proximity dependencies identified.*	-
Human and organizational dependencies		
Common maintenance team	*Only considered for identical components dependencies.*	-

The quantitative screening is then performed for dependencies by calculating the maximum contribution to the multi-unit core damage frequency (MUCDF) for each one of the dependencies according to:

$$MUCDF_{i,ux} = FV_{i,ux} \times CDF_{ux}$$

The total core damage frequency for the included initiating events is calculated for each unit (1.7E-4). The representative basic event(s) are identified in the PRA model and their Fussell-Vesely (FV) values calculated as shown in Table A-5.

Table A-5 – Quantitative screening of dependencies

Identified dependencies	**Representative basic event(s)**	**Comment**	**FV**	**MUCDF [1/yr]**
Identical components				
Diesel generators	CCF-ACP-DG---A-ALL (CCF)	CCF only for failure mode 'fails to start'	3.7E-2	6.3E-6
Service water pumps	CCF-SWS-PM---A-ALL (CCF)	CCF only for failure mode 'fails to start'	3.6E-1	6.1E-5

With a MUCDF screening criterion equal to 1.0E-8/year none of the identified dependencies can be screened out at this stage.

Regarding the selection of initiating events, it is assumed that none of the single unit initiating events (SUIE) can propagate to the other unit. They are therefore screened out as potential multi-unit initiators. The already identified multi-unit initiating event (MUIE), multi-unit loss of offsite power, has a frequency larger than 1.0E-8/year and will therefore be included in the analysis.

Step 3 – Probability estimation

There are two diesel generators and two service water pumps per reactor unit. The fraction of diesel generator or service water pumps failures involving common cause failures shared with the other diesel generator or service water pump respectively within a unit is 0.1 (β) according to the single unit PRA. An assumption is made that one out of ten common cause events of diesel generators and service water pumps would impact all four components in respective case, i.e. there are one common cause event with four component failures (n_4) and nine common cause events with two component failures (n_2). The fraction of common cause failures involving failure of all four components is calculated according to [3]:

$$\beta' = \frac{4n_4}{4n_4 + 2n_2}$$

The probability for a multi-unit CCF is then calculated according to:

$$MUCCF = \beta' \beta Q$$

Using the failure probabilities for a diesel generator and a service water pump from the PRA model the probability of a multi-unit CCF can be estimated, see Table A-6.

Table A-6 – Estimation of multi-unit CCF probabilities

Dependence	CCF event	β'	β	Q	Multi-unit CCF probability
Diesel generators	EDG-MUCCF	1.8E-1	1.0E-1	8.6E-3	**1.5E-4**
Service water pumps	SWS-MUCCF	1.8E-1	1.0E-1	1.2E-3	**2.2E-5**

The frequencies of loss of the diesel generators and service water pumps are also needed. The estimation is based on the same principle as above – using the failure rate of the equipment (diesel generator: 2.0E-1/year; and service water pump: 3.1E-2/year) and the CCF factors. The repair time for the combination is assumed to be 24 hours for both diesels and service water pumps. They frequency is hence 3.6E-3/year for the diesel generators and 5.6E-4/year for the service water pumps.

The multi-unit event combinations that should be considered in the analysis are listed in Table A-7.

Table A-7 – Identified multi-unit event combinations

Multi-unit event combinations
Multi-unit event combinations w/o MUIE
EDG-MUCCF
SWS-MUCCF
EDG-MUCCF, SWS-MUCCF
Multi-unit event combinations w/ MUIE
LOOP
LOOP, SWS-MUCCF
LOOP, EDG-MUCCF
LOOP, EDG-MUCCF, SWS-MUCCF

Step 4 – Extension of unit PRA models

Since the gas turbine system is shared between the units and may not be able to support the both units the system is only credited for unit 1. In the unit 2 model, the basic events representing failure of the gas turbines identified in step 2 is therefore set to true.

No other modifications are made to the models in this example.

Step 5 – Screening of events and event combinations

The multi-unit event combinations without a multi-unit initiator include the combination of the multi-unit CCFs on diesel generators and service water pumps respectively. According to step 3 the estimated CCF frequency is 3.6E-3/year for the diesel generators and 5.6E-4/year for the service water pumps. The multi-unit event combinations with one CCF only are kept in the analysis. The combination with CCF on both emergency diesel generators and service water pumps is assumed to be screened out based on low frequency and in combination with the repair time for the combination of events (this calculation is not shown in this example, but is assumed to be insignificant).

The multi-unit event combinations with a multi-unit initiator that are identified, in this example multi-unit loss of offsite power, are modelled in an event tree according to Figure A-1. Frequencies and probabilities estimated in step 3 are used to calculate the frequency for each sequence.

Multi-unit loss of offsite power	Emergency diesel generator multi-unit CCF	Service water pump multi-unit CCF				
MU-LOOP	ACPDG MUCCF	SWS MUCCF	No.	Freq.	Conseq.	Code
			1	1,00E-01		
			2	2,20E-06		SWS MUCCF
			3	1,50E-05		ACPDG MUCCF
			4	3,30E-10		ACPDG MUCCF-SWS MUCCF

Figure A-1. Event tree representing multi-unit event combinations that contain multi-unit loss of offsite power initiating event.

The frequency of the event combination containing multi-unit loss of offsite power and multi-unit CCFs on the emergency diesel generator and the service water pumps is sufficiently low, 3.3E-10/year, that it can be screened out from further analyses. The three other sequences will be kept in the analysis.

Step 6 – Computation of conditional accident probabilities

For single unit initiating events, in this example large loss of coolant accident (ALOCA) and loss of main feedwater (LMFW), the conditional core damage frequency (CCDF) is calculated by setting the basic events representing the dependencies (see steps 2 and 3) to true in the PRA model. The conditional core damage probability is then calculated according to:

$$CCDP = 1 - e^{-CCDF \times t}$$

The assumption is made that the repair time (t) for both the diesel generators and the service water pumps is 24 hours respectively. Table A-8 summarizes the CCDF and CCDP for the studied dependencies for both reactor units.

Table A-8 – CCDF and CCDP for multi-unit event combinations w/o MUIE

Multi-unit event combination w/o MUIE	CCDF unit 1 [1/year]	CCDF unit 2 [1/year]	CCDP unit 1	CCDP unit 2
EDG-MUCCF	1.3E-3	1.3E-3	3.6E-6	3.6E-6
SWS-MUCCF	5.0E-1	5.0E-1	1.4E-3	1.4E-3

For the multi-unit initiating events, in this example only loss of offsite power (LOOP), the conditional core damage probabilities are calculated in the PRA model by setting the different events to true, see Table A-9.

Table A-9 – CCDP for multi-unit event combinations w/ MUIE

Multi-unit event combination w/ MUIE	CCDP unit 1	CCDP unit 2
MU-LOOP	2.3E-4	3.8E-3
MU-LOOP, SWS-MUCCF	6.1E-2	1.0
MU-LOOP, EDG-MUCCF	6.1E-2	1.0

We can notice the difference in CCDP due to that the gas turbine system is only accounted for in unit 1.

Step 7 – Computation of risk metrics of multi-unit event combinations

The contribution to the MUCDF from multi-unit event combination without MUIEs is calculated according to:

$$MUCDF(BE_1, BE_2, \dots, BE_M) = f_{BE_1, BE_2, \dots, BE_M} \cdot \prod_{i=1}^{n} CCDP_i(BE_1, BE_2, \dots, BE_M)$$

The frequencies for the dependencies were estimated in step 3. These frequencies are then multiplied with the conditional core damage probabilities calculated in step 6 as shown in Table A-10.

Table A-10 – Contribution to MUCDF for multi-unit event combinations w/o MUIE

Multi-unit event combination w/o MUIE	f [1/year]	CCDP unit 1	CCDP unit 2	MUCDF [1/year]
EDG-MUCCF	3.6E-3	3.6E-6	3.6E-6	**4.7E-14**
SWS-MUCCF	5.6E-4	1.4E-3	1.4E-3	**1.1E-09**

For the multi-unit event combinations with a MUIE the event tree constructed in step 5 is used to calculate the contributions to the MUCDF. The frequencies in the event tree sequences that have not been screened out are multiplied with the conditional core damage probabilities calculated in step 6 according to:

$$MUCDF - LOOP - Sequence1 = f_{LOOP} \times (1 - p_{EDG-MUCCF}) \times (1 - p_{SW-MUCCF}) \times CCDP_1(LOOP) \times CCDP_2(LOOP)$$

$$MUCDF - LOOP - Sequence2 = f_{LOOP} \times (1 - p_{EDG-MUCCF}) \times p_{SWS-MUCCF} \times CCDP_1(LOOP, SWS - MUCCF) \times CCDP_2(LOOP, SWS - MUCCF)$$

$$MUCDF - LOOP - Sequence3 = f_{LOOP} \times p_{EDG-MUCCF} \times (1 - p_{SW-MUCCF}) \times CCDP_1(LOOP, EDG - MUCCF) \times CCDP_2(LOOP, EDG - MUCCF)$$

The resulting MUCDF values are shown in Table A-11.

Table A-11 – Contribution to MUCDF for multi-unit event combinations w/ MUIE

Multi-unit event combination w/ MUIE	f*dependencies [1/year]	CCDP unit 1	CCDP unit 2	MUCDF [1/year]
LOOP-Sequence 1	1.0E-1	2.3E-4	3.8E-3	**8.7E-8**
LOOP-Sequence 2	2.2E-6	6.1E-2	1.0	**1.3E-7**
LOOP-Sequence 3	1.5E-5	6.1E-2	1.0	**9.2E-7**

Step 8 – Construction of new multi-unit model

No dependencies requiring a separate multi-unit model have been identified in this simplified example.

Step 9 – Computation with multi-unit model

Since no new multi-unit model has been constructed in step 8, no additional computation has to be made.

Step 10 – Computation of multi-unit accident frequency and event importance

All contributions to the MUCDF from step 7 (step 9 is not relevant in this example) are summed up to calculate an approximate multi-unit core damage frequency in Table A-12. Table A-13 presents Fussell-Vesely values of different multi-unit events.

Table A-12 – Computation of total MUCDF

Multi-unit event combination	MUCDF [1/year]
Multi-unit event combinations w/o MUIE	
EDG-MUCCF	4.7E-14
SWS-MUCCF	1.1E-9
Multi-unit event combinations w/ MUIE	
LOOP-Sequence 1	8.7E-8
LOOP-Sequence 2	1.3E-7
LOOP-Sequence 3	9.2E-7
Total	**1.1E-6**

Table A-13 – Fussell-Vesely values of multi-unit events

Multi-unit event	Fussell-Vesely
MU-LOOP	1.0
EDG-MUCCF	0.84
SWS-MUCCF	0.12

The importance of the multi-unit dependence for the gas turbine system, which is only credited in unit 1 since it cannot support both units at the same time, could be estimated by including the failure of the gas turbine in the multi-unit event combinations. In this small example, we can estimate the importance other way since we know that the gas turbine failure completely dominates the risk in the LOOP sequence 3 (LOOP with MUCCF on EDG).

Hence, by a rough estimate the importance of the gas turbine is the same as the importance of the multi-unit CCF of the diesels.