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Common Cause Failure Analysis

Improved Approach for Determining the Beta
Value in the PDS Method

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Reliability, Availability, Maintainability and Safety (RAMS)
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MASTER THESIS

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Preface

This master thesis has been carried out at the Department of Mechanical and Industry Engineering, Faculty of Engineering, Norwegian University of Science and Technology (NTNU) during the spring semester in 2017. This thesis is a part of the two-year international master's program Reliability, Availability, Maintainability and Safety (RAMS).

A single common cause failure (CCF) can lead to the failure of a system, even though the system consists of redundant components. A large number of researches have been conducted and several models have been developed to assess CCFs for decades. One recent study of SINTEF suggested a new CCF estimator (PDS estimator) to overcome several challenges of conventional CCF estimators. However, the new PDS estimator also has couple of challenges that come from several assumptions. To improve the PDS estimator, these assumptions and challenges need to be investigated with providing proper solutions.

It is assumed that reader has basic knowledge in RAMS.

Trondheim, 2017-06-16

Kwi Yeon Koo

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I would like to express my deepest gratitude to my supervisor Professor Mary Ann Lundteigen at NTNU. Her excellent guidance and support were very helpful to finish this thesis. Especially, she has encouraged me when I lost confidence, and given valuable advice not only academic but also practical guidance.

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Finally, I would like to thank my family for being helpful and supportive during Master program.

K.Y.

Summary

This master thesis investigates definitions and classifications of the common cause failure from various industries. From the investigation, four core aspects of the definition for the common cause failure are extracted, and improved classifications for root causes and coupling factors of the common cause failure are suggested.

This thesis also explores a framework for the inclusion of the impact of the common cause failure in risk and reliability evaluations. From the investigation of the framework, the relationship among definition of the common cause failure, causes of the common cause failure, common cause failure parametric model, parameter estimation and system model is provided.

Especially, this thesis focuses on the common cause failure parametric model that is used to quantify common cause failure effect on the risk assessment. The thesis investigates popular common cause failure parametric models (Beta Factor model, Alpha Factor model, Multiple Greek Letter model, and Multiple Beta Factor model.), and discusses their features.

After the investigation of common cause failure parametric model, this thesis focuses on the Beta Factor Model and its parameter estimation. For the parameter estimation, two conventional approaches (data based and checklist based) and a relatively new approach (PDS method) are presented.

The main contribution of this thesis is i) to identify challenges of the PDS estimator in the PDS method and ii) to suggest improved approach for determining the value of PDS estimator. This thesis identifies underlying assumptions and constraints in PDS estimators, and proposes improved approach to determine CCF group size. Case study is conducted to apply this improved approach. This new approach is realized as a computer program using Microsoft Excel and its embedded Visual Basic, so that the industries can easily use the new approach.

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Chapter 1

Introduction

1.1 Background

Redundancy[1] is one of the most commonly used concepts to achieve high reliability of a system. In order to compose successful redundancy, independence between redundant components should be ensured. If they share some dependency in terms of design, manufacture, external environment, etc., it is possible that a single condition or event can trigger fault states in more than one component, regardless of the type of the redundancy [2]. This is called as common cause failures (CCFs).

Many reliability studies have shown that the presence of CCF tends to increase system failure probabilities [3-6]. In addition, without careful insight, the system reliability assessment with CCF events[2] may lead to overestimated system reliability, which makes reliability analysis less effective in the system design. Therefore, it is important to model precisely CCF effects on the system reliability analysis.

For this reason, the treatment of CCFs have been a key topic in reliability assessments of systems that involve redundant components since 1970s [1]. There have accordingly been a lot of research on the topic for the CCFs.

Especially, the CCF events are major elements of incidents and accidents in the nuclear industry [8]. So, the nuclear industry has developed the most advanced theories and methodologies for

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[1] Redundancy means having two or more items, such that if one item fails, the system can continue to function by using the other item(s) [1]

[2] CCF event is defined as that a failure event where at least two components fail due to a common cause [7].

the CCF analysis. The U.S. Nuclear Regulatory Commission[3] (NRC) has published the important regulatory guides that include a comprehensive study of the CCF analysis as a part of risk assessments. For instance, Mosleh, et al. [9] provide a procedure framework for CCF analysis. Marshall, et al. [10] present the CCF parameter estimates for the risk important safety systems and components in commercial nuclear power plants. The collection of CCF data and estimation of CCF parameters are shown in Marshall, et al. [11].

The aviation, oil & gas and aerospace industry have paid attention to CCFs as well. In the aviation industry, IEC 61508-6 is referred to analyse the CCF. IEC 61508 provides a check-list methodology to quantify the effect of CCFs on the system unavailability[12, 13]. The Norwegian offshore oil and gas industry has paid attention to CCFs of SISs since the 1990s [14, 15]. To improve the quality of CCF calculation, Hauge, et al. [15] suggest more realistic data for CCFs and equipment specific checklists as a part of PDS method[4].

There are many other researches on the CCF analysis. A number of studies have investigated causes of CCFs, such as Paula, et al. [16], Parry [17], NEA [18], Childs and Mosleh [19], etc. One of important factors for CCF analysis is to determine parameters of the CCF model. For parametric modelling of CCFs, the beta-factor model [20, 21], the binomial failure rate model [21, 22], the alpha-factor model [23, 24], the multiple Greek letter model [4], the multiple beta-factor model [25], and many other models and methods have been introduced.

The parameter estimation is generally based on operational database with mathematical model and/or combination of field data, generic values made from data handbook, and expert judgements (check-list). The nuclear industry is the only industry sector that has run a major project on collecting CCF data [7], and they estimate the parameters base on the field data and generic values. In oil & gas and aviation industry, historical CCF data is deficient and very few data sources are available on parameter estimation. The parameter estimation is therefore generally based on expert judgements and/or experience from the nuclear industry, rather than practical operational data from field [26, 27].

A recent study by SINTEF suggests a combined approach to obtain more realistic CCF estimator that is called as PDS estimator [26]. The PDS estimator is obtained by the

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[3] The U.S. Nuclear Regulatory Commission (NRC) is an independent agency of the United States government tasked with protecting public health and safety related to nuclear energy. The NRC regulates commercial nuclear power plants and other uses of nuclear materials, such as in nuclear medicine, through licensing, inspection and enforcement of its requirements. See https://www.nrc.gov/about-nrc.html

[4] PDS method is developed to quantify the safety unavailability and loss of production for safety instrumented systems (SISs) by SINTEF with industries. It is explained in detail in section 2.7

combination of operational data, generic value, and checklist. As mentioned above, the nuclear industries use operational data and generic data to obtain CCF parameters, while the oil & gas industries derive CCF parameters by using checklists, expert judgements and/or methods used in oil & gas industry (PDS method). PDS method combines these approaches and suggests a new approach to strengthen the strength and make up for the weakness of the two different industries.

Even though the PDS estimator contributes to improve the accuracy of the CCF analysis, it still has several limitations due to some assumptions that are caused by incomplete data, complexity of CCF attribute, uncertainty, etc. It is therefore needed to identify the limitations and improve the PDS estimator.

1.2 Objectives

Main objective of this master thesis is to identify limitation of PDS estimator and to suggest an improved approach for determining the value of beta-factor in the PDS method.

To meet this objective, the following tasks are to be carried out:

1) Provide fundamental understanding of the CCFs (definition and causes of CCF).
   This basic knowledge is essential to following objectives.
2) Describe how CCF events are treated in the risk assessment.
   This objective is necessary to apply CCF knowledge in the real industry case.
3) Investigate and discuss CCF parametric models, including limitations.
   CCF parametric models are used to quantify the CCF events. For accurate calculation of system reliability, it is important to understand the CCF parametric models and its limitation.
4) Investigate and discuss PDS estimator, including limitations.
   Even though the PDS estimator is improved from existing CCF parametric model, it still has several limitations. It is therefore needed to identify the limitations and improve the PDS estimator.
5) Suggest improved approach for determining the PDS estimator, and conduct case studies

1.3 Limitation

This master thesis investigates overall CCF analysis procedure that consists of qualitative and quantitative approach. The thesis focuses on the quantitative CCF analysis, above all, the CCF parametric model are studied.

To investigate that how CCFs are treated in risk assessment, only literature from nuclear industry have been reviewed.

The main contribution of this master thesis focuses on improvement of an approach for estimating values of beta for PDS method only. Other CCF models, like Beta Factor model, Alpha Factor model, Multiple Greek Letter model, etc., will be mentioned briefly with basic concepts.

1.4 Research method

General research approaches are mainly based on literature study, and mathematical computation programs is used additionally. The main approach is as follows;

- Objective 1, 2, 3 and 4 will be established through review of literature in nuclear and oil & gas industries
- For the objective 4 and 5, run experiments i) to investigate underlying assumptions and constraints in PDS estimators for beta factor and ii) to suggest improved approach to obtain CCF group size
- Suggested approach is realized as a computer program using Microsoft Excel and its embedded Visual Basic.
- Conduct case studies to apply the suggested methodology (input data for the case study is referred from the SINTEF report)

Improvements are suggested mainly based on reasonable inference and sufficient productive discussions.

1.5 Structure of thesis

This master thesis is organized as follows; Chapter 2 provides the fundamental knowledge of CCF (definition and causes of CCF), and how CCFs are treated in risk assessment. An explicit and implicit approach for incorporating CCF into the system logic model is also presented. In addition, popular parametric models are introduced with its limitations. Chapter 3 provides that how to estimate β in the standard beta factor model, its limitations and the necessity of improvement. The background of the PDS estimator and how to derive it are also presented. Chapter 4 The limitation of the PDS estimator is discussed and improved approach for determining of PDS estimator is suggested. Chapter 5 is related to the description of the case study. Application of the suggested methodology and results are presented. Finally, results, conclusion and possible future works are presented in Chapter 6.

Chapter 2

Overview of CCF

Prior to the investigation of CCF effects on the risk assessment, it would be helpful to review basic concepts of the CCF. During fall semester in 2016, the specialization project was conducted to contribute with some new knowledge about “what a CCF is” through studying the definition, classification, causes, and examples of CCFs. Section 2.1 and 2.2 are based on the specialization project.

2.1 Definition of CCFs

To study effects of CCF on the system reliability, there is a need to understand the definition and causes of CCF. There is no globally agreed definition of CCFs. This implies that people in different industry sectors may have different opinions of what a CCF event is [1]. Several definitions of CCFs in different industries are introduced below;

- Nuclear industry (NUREG/CR 6268) [28]
  Dependent failure in which two or more component fault states exist simultaneously, or within a short time interval, and are a direct result of a shared cause
- Space industry [29]
  The failure (or unavailable state) of more than one component due to a shared cause during the system mission
- Oil and gas industry [26]
  Components/items within the same component group that fail due to the same root cause within a specified time

- IEC 61508 [30]
  Failure, that is the result of one or more events, causing concurrent failures of two or more separate channels in a multiple channel system, leading to system failure
- IEC 61511 [31]
  A failure which is the result of one or more events, causing failures of two or more separate channels in a multiple channel system, leading to a system failure

Smith and Watson [32] reviewed nine different definitions of CCF and suggested that a definition of CCF must encompass the following six attributes;

1) The components affected are unable to perform as required
2) Multiple failures exist within (but not limited to) redundant configurations
3) The failures are "first in line" type or failures and not the result of cascading failures
4) The failures occur within a defined critical time period
5) The failures are due to a single underlying defect or a physical phenomenon
6) The effect of failures must lead to some major disabling of the system's ability to perform as required

Rausand [14] suggested a new definition of CCF, by combining the two definitions from nuclear industry [28] and IEC 61508 [30], as below;

> Failure, that is the direct result of a shared cause, in which two or more separate channels in a multiple channel system are in fault state simultaneously, leading to system fault.

While there are some differences in various definitions of CCFs, the definitions have four main points in common.

1) Occurrence of multiple failures
2) Multiple failures lead to system failure
3) Within a specific time period
4) Due to a shared cause

In this thesis, the CCF includes above four attributes when the CCF is not related with PDS method. In the PDS method, the CCF is defined with a broader boundary as follow; components/items within the same component group that fail due to the same root cause within a specified time [26]. With this definition, it is emphasized that CCFs may not lead to system failure. For instance, in a 2oo4 system, two components may fail due to a common cause, but the system will be still available. Therefore, the definition of CCFs in PDS method does not include “2) Multiple failures lead to system failure” of above four attributes of CCFs.

2.2 Causes of CCFs

Causes of CCFs can be classified into two categories as below [1, 16, 17];

1) Root cause: the most basic cause that, if corrected, would prevent recurrence of this and similar failures
2) Coupling factor: a property that makes multiple components susceptible to failure from a single shared cause

Coupling factor is a property that causes multiple failures due to a same root cause. Without coupling factor, a single root cause cannot cause multiple component failures. Therefore, if we can eliminate coupling factors of a system, then we can prevent CCFs from occurring. Relation between root cause and coupling factor is illustrated in Figure 1.

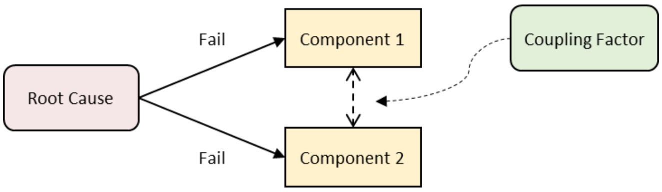

Figure 1: Root cause and coupling factor of CCF

A number of studies has surveyed root causes and coupling factors of CCF events [1]. Some representative classification of CCF root causes and coupling factors are proposed by NUREG/CR 6268 [28], Paula, et al. [16], NEA [18] and US DOE [33] which are listed in Appendix B. The relationship among these classifications is illustrated in Figure 2.

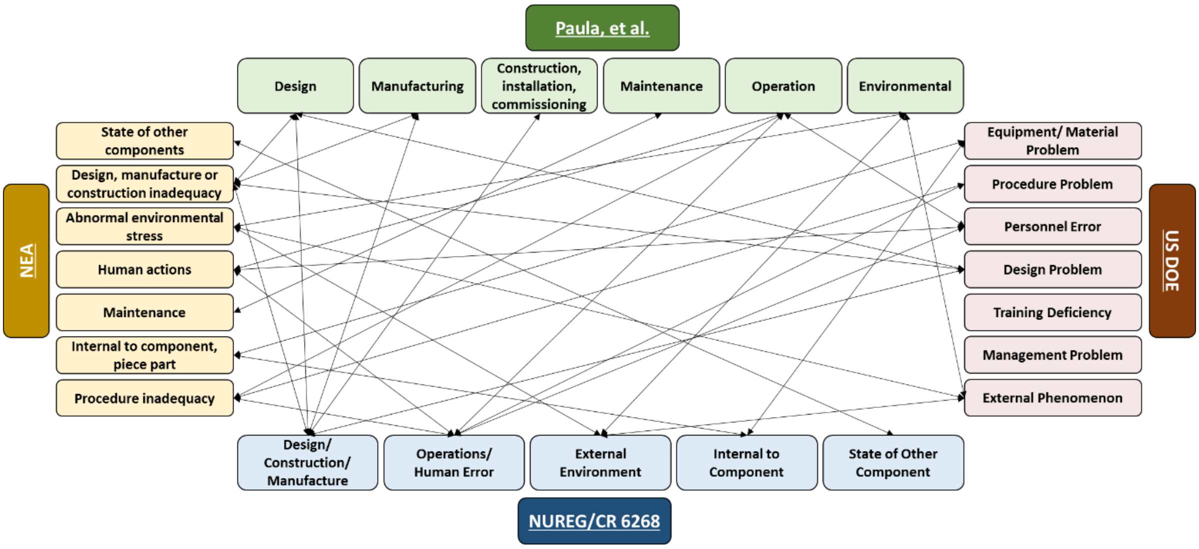

Figure 2: Relationship among CCF root cause classifications

Total 25 root-causes categories are provided by the four studies. Some categories overlap each other, while others are unique in some studies. Design, human error (operation), and external environment are included in all of the four studies, while training deficiency and management problems are considered by US DOE [33] only. One possible use of this relationship is to prioritize the root-cause categories in order of appearance, when we have limited resources and need to focus on a few critical CCF root causes. However, we must carefully use this approach, because the high number of appearance does not necessarily mean the importance of a root-cause category. For instance, ‘Human error’ exists in all the four studies (Human action, operations/human error, personnel error, and operation). However, in case of an autonomous vehicle or ship, the effect of human operation is limited, and is not critical cause of system failure. On this wise, the application can vary depending on operating conditions and industrial needs.

The classifications of CCF coupling factors are listed in Appendix C. The classification of CCF coupling factors closely parallels the classification of CCF root causes. The classifications of CCF coupling factors include *Hardware*, *Operation*, *Environment*, *Maintenance*, *Design*, etc. that are included in the classification of CCF root causes. We can thereby infer that CCF coupling factors can be classified similarly to CCF root causes. One major difference is that coupling factors include “same”. For instance, wrong maintenance procedure can be a root cause, while *same* maintenance procedure is a coupling factor.

All the CCF root cause categories, investigated above, have single level of hierarchy, and this causes confusion and overlaps. For instance, root cause category of NEA [18] includes *Maintenance* and *Procedure inadequacy*. However, the two root-causes categories are not in a same level. *Maintenance error* can occur due to *Procedure inadequacy*. The two categories should not be placed in a same level. We need multiple levels of categories for these root causes.

With the concept of multiple levels of categories, we can first classify CCF root causes into three categories: *Hardware, Human, and Environment*. *Hardware* based CCF root causes can further be developed into *Design*, *Realization of design*, and *Other components*. *Realization of design* can finally be split into *Manufacture*, *Installation*, *Construction*, and *Commission*. *Human* based CCF root causes have two categories: *Operation* and *Maintenance*. Both of them can have three sub-categories: *Procedure*, *Management*, and *Training*. *Environment* based CCF root causes can be classified into *Internal environment* and *External environment*. This new classification of CCF root causes is illustrated in Figure 3. This new classification integrates all root causes that are introduced in above four studies (NUREG/CR 6268 [28], Paula, et al. [16], NEA [18] and US DOE [33]). This hierarchy structure may contribute better understanding of CCF root causes.

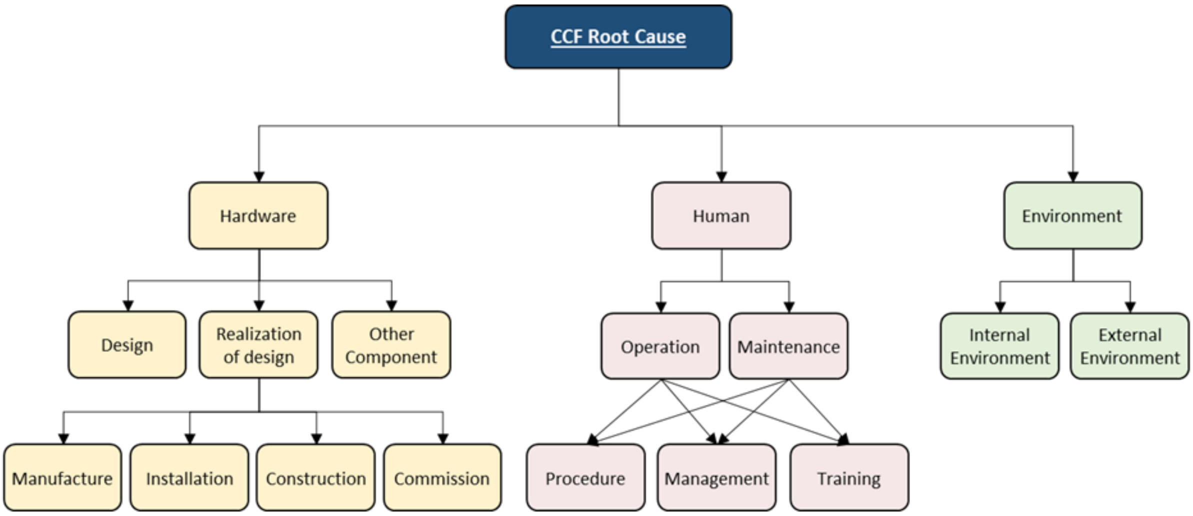

Figure 3: Proposed classification of CCF root cause

The two main criteria to distinguish root causes are “When/How” and “What”, as shown in Figure 4. “When/How” is a general criterion that classifies the root causes. Proposed classification given in Figure 3 is about “When/How” of root causes. “What” is an equipment specific criterion that varies depending on the system, condition, industry, etc. For instance, a wrong operation procedure is “When/How”, and a reversed sequence of shutdown valves is “What”.

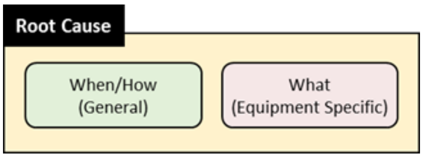

Figure 4: Two criteria of root cause

The classification of CCF coupling factors shares many part of the classification of CCF root causes in Figure 3. Similar to the root cause, new classification of the coupling factor is illustrated in Figure 5, and this classification combines all coupling factor from four studies (NUREG/CR 6268 [28], Paula, et al. [16], NEA [18] and US DOE [33]) and creates a hierarchical structure. CCF coupling factors can first be divided into *Hardware*, *Human, and Environment*, just like the first categories of CCF root causes. *Hardware* based CCF root causes can further be developed into *Design*, *Realization of design*, and *Other components*, still same with CCF root cause categories. The differences are: (1) *Design* can be split into *Physical appearance*, *Layout*, and *Configuration*, (2) *Operation* is divided into *Procedure* and *Staff*, and (3) *Maintenance* includes *Procedure*, *Staff*, and *Schedule*.

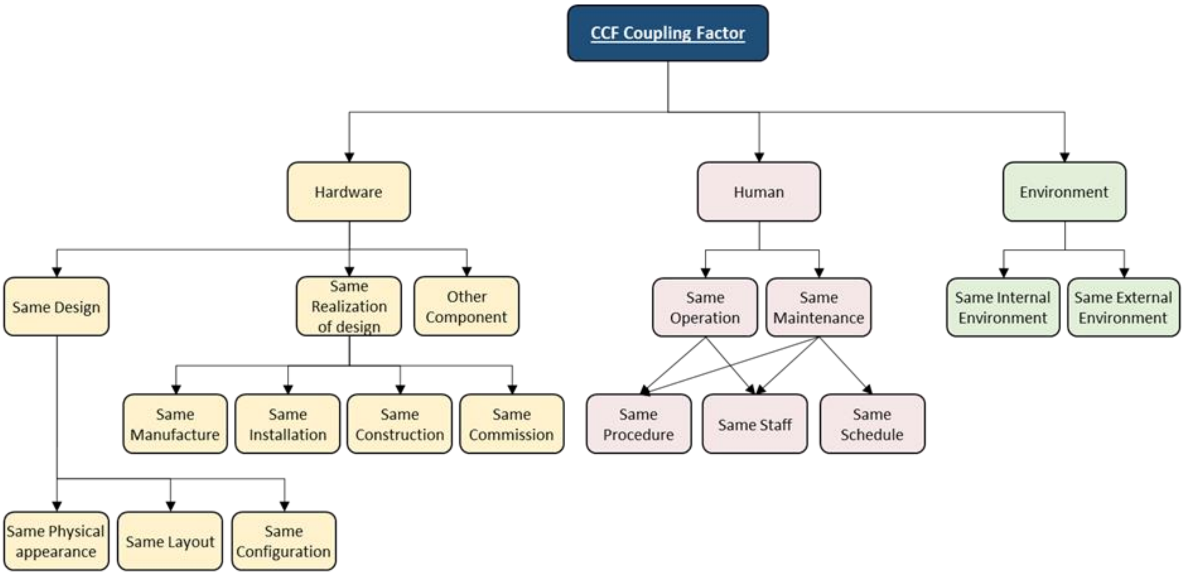

Figure 5: Proposed classification of CCF coupling factor

2.3 Treatment of CCFs in risk assessment

There are many key literatures in the nuclear industry. In this section, literatures from Nuclear Regulatory Commission (NRC) was reviewed in order to give an overview of the treatment of CCFs in risk assessments. NRC has published the important regulatory guides about the CCFs. NUREG/CR 4780 [9] provides considerable guidance on how to perform and document a CCF analysis. To understand the concepts associated with CCF and how to defend against them, NUREG/CR 5460 [34] discusses the cause-defence methodology for CCF analysis and prevention. NUREG/CR-5485 [8] presents updated procedural framework of NUREG/CR-4780 [9] for use in applied risk and reliability evaluations. NUREG/CR-4780 [9] and NUREG/CR-5485 [8] have been viewed as too time consuming [11], because despite wide acceptance of the basic approach. To overcome this, a CCF data collection and analysis system have been developed. This analysis system includes a method for identifying CCF events, coding and classifying those events for use in CCF studies, and analysing the data. The system is designed to run on a personal computer. NUREG/CR-6268 [11] describes this system and summarizes how data are gathered, evaluated, and coded into the CCF system, and provides the process for using the data to estimate probabilistic risk assessment common-cause failure parameters. To quantify the CCF events and estimate the CCF parameters, NUREG/CR-5497 [10] presents the CCF parameter estimates for the risk important safety systems and components in commercial nuclear power plants. CCF insights for emergency diesel generators, motor-operated valves, pumps, and circuit breakers are presented in [35-38]. The relationship between these NUREG standards are shown in Fig. 6.

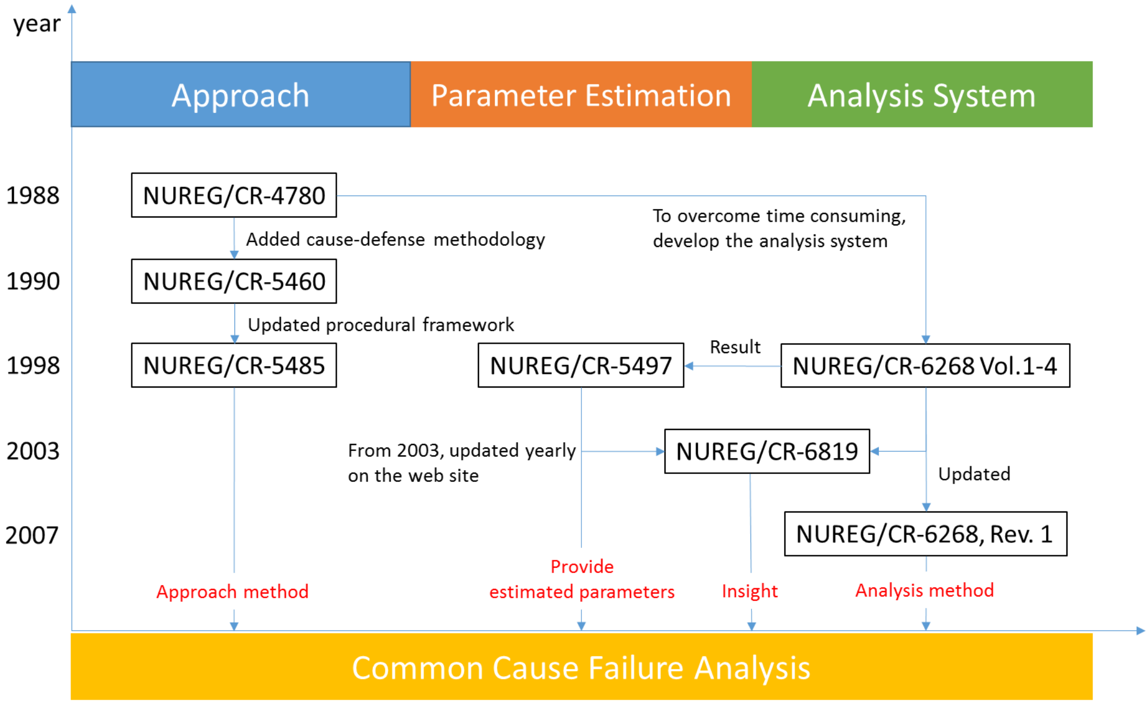

Figure 6: The relationship between NUREG standards

A structural framework for the modelling of the CCF events are first developed in the NUREG/CR-4780 [9] (Fig. 7). In Figure 7, corresponding sections in this thesis are indicated. Stage 1 and 2 are qualitative approach, whereas Stage 3 and 4 are the quantitative approach.

In stage 1 and 2, we need to define the system of interest, boundary condition, basic events, and any other assumptions for analysis. It will be too complicate if we consider all possible failure combinations. In this process, the CCF events that are not applicable to the assessment are eliminated based on the definition and causes of the CCFs.

In stage 3, we need to define common cause basic events[5] (CCFBEs) based on the results of the stage 1 and 2, then defined CCFBEs are included in the system logic model which is developed in Stage 1. The CCFBEs can be implemented in explicitly or implicitly. If causes of the CCFs is defined clearly, CCFs can be simply included in the system logic model (e.g., Fault Tree, reliability block diagram, event tree, etc.) explicitly. Meanwhile, if it is difficult to model CCFs explicitly, we can use CCF parametric models to assess CCFs implicitly [1].

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[5] Common cause basic events are basic events that represent failures of specific components in a common cause component group [9].

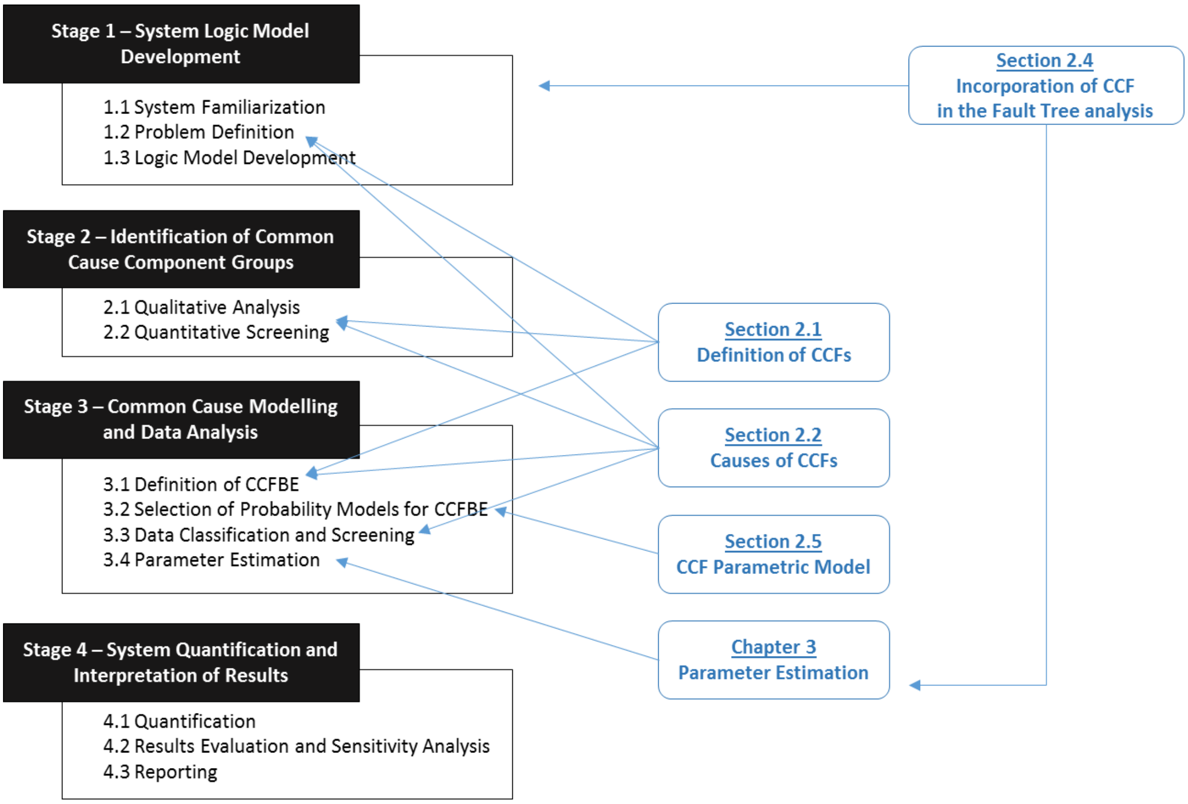

Figure 7: Framework of CCF analysis and corresponding sections in this thesis

The relationship between the definition and causes of CCF, CCF parametric model and the system model is show in Figure 8. To implement the effect of CCF in the system model, we need to quantify the CCFs. To quantify the CCF, we need to select a CCF parametric model that will be used in the quantification of the CCFBEs. Detailed description of the CCF parametric model is presented in section 2.5. We can select CCF model based on the definition of the CCF. For instance, if we define that a common cause always leads to the failure of entire components in a CCF group[6], then the standard beta-factor model will be selected. If we specify that some components in a CCF group can survive after a CCF event, then we can select one of Alpha-factor, Multiple Greek letter and Multiple beta factor model. These models are well documented in NUREG/CR-4780 [9], and the features of these models are described in section 2.5.

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[6] A CCF group is a group of components that the risk analyst considers to be subject to shared causes of failure. A common cause component group (CCCG) is a group of components, which share coupling factors, making them susceptible to a common failure cause [9].

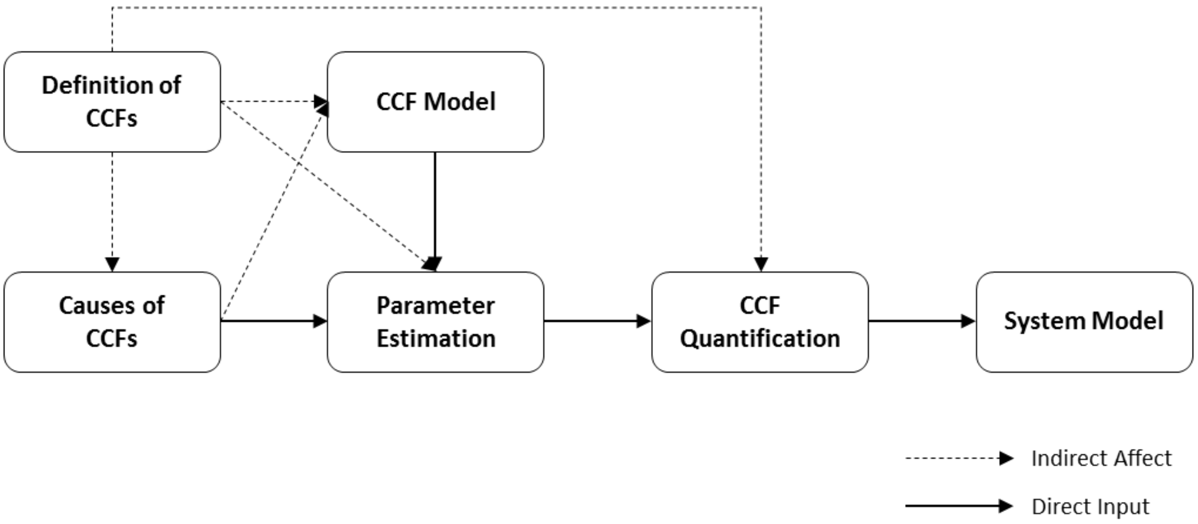

Figure 8: The relationship between the definition and causes of CCF, CCF parametric model and the system model

2.4 Incorporation of CCF in the Fault Tree Analysis

As previously stated, there are two way to implement the CCFs in the system model; i) implicitly ii) explicitly. For instance, consider a system that consists of two pressure transmitters with 1oo2 configuration (Fig. 9).

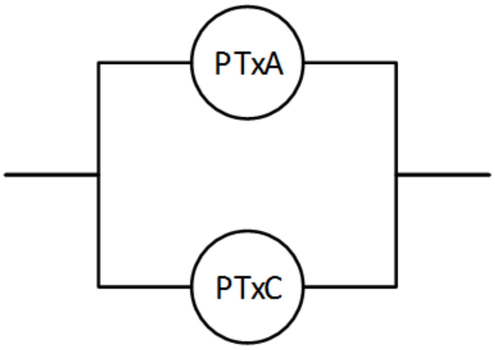

Figure 9: Two pressure transmitters with 1oo2 configuration

If we can clearly define causes of CCFs like vibration, fire, wrong maintenance, etc., then the defined causes are treated as basic events under the common cause failure. Therefore, the system fault tree is expended with extra CCF events, as shown in Figure 10.

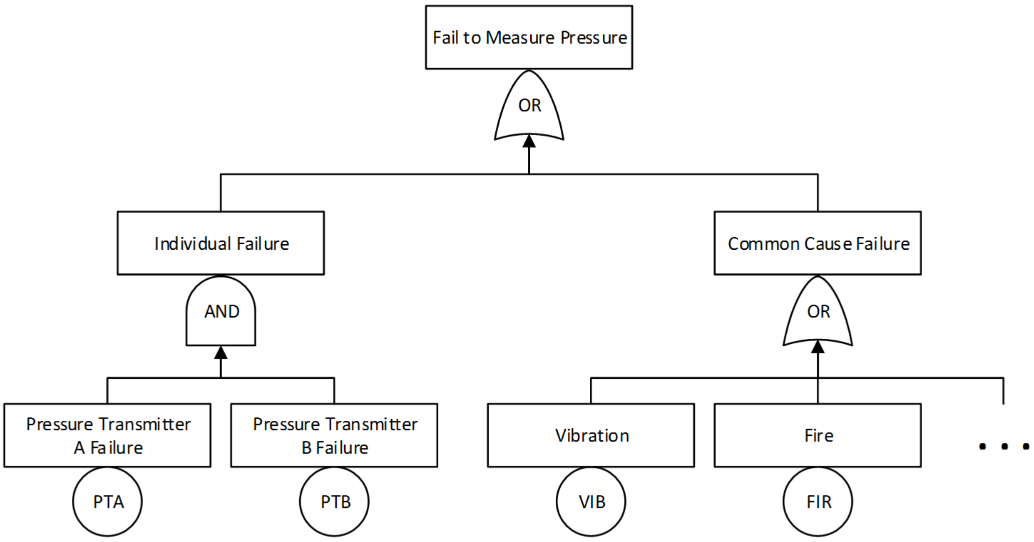

Figure 10: Fault tree with explicit CCFBEs

However, some causes of the CCFs are difficult or even impossible to identify and model explicitly [1], because it is normally difficult to find out all causes of CCFs. Under this condition, CCFBEs are implemented in the system logic model in the form of parameters (e.g., α, β, or any other Greek letters).

For instance, consider a system that consists of three identical pressure transmitters with 2oo3 configuration (Fig. 11). A system model for the pressure transmitters system is built in Figure 12.

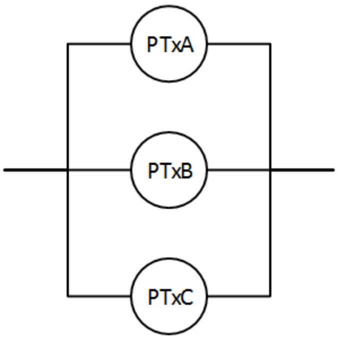

Figure 11: Three transmitters with 2oo3 configuration

Vaurio [39] explains well about the implicit approach for incorporating CCF into system analysis. In the implicit method, first the fault tree is built without considering CCF (blue part in Fig. 12). To include the CCFs into the Fault Tree, each component is expanded down to divide a component into a dependent and independent portion. The relationship between dependent and independent portion is determined according to the selected parametric model.

If we select the Beta Factor model, intermediate values of the multiplicity for the failure event are not considered. There is therefore only one CCFBE ($CCF_A = CCF_B = CCF_C$ in green part in Fig. 12).

If we assume that CCF can lead to either two to three components failure simultaneously, then transmitter A is expanded to the independent portion (A_I) and the dependent portion (C_{AB}, C_{AC}, and C_{ABC}) (orange part in Fig. 12). Same expansion is applied to transmitter B and C.

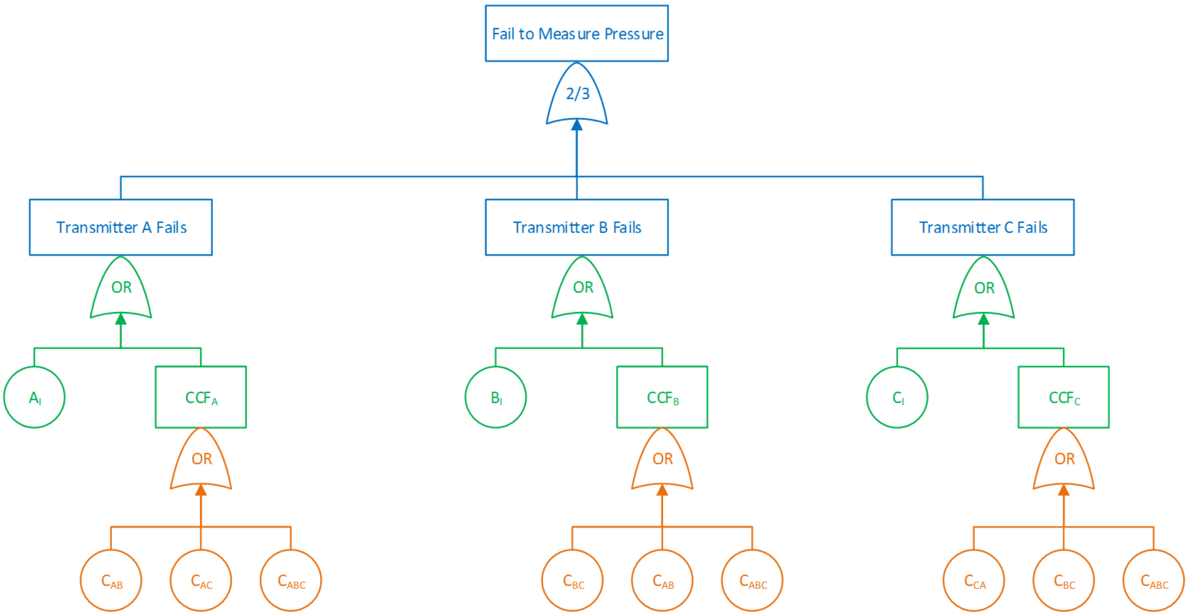

Figure 12: Fault tree of the 2oo3 pressure transmitter system

Depending on the selection of the CCF parametric model, the system unavailability is calculated different way. It is well described in [40] that how to calculate the system unavailability according to selected CCF parametric model. The rest of this section refers to [40].

By using the rare events approximation[7], the probability of the pressure transmitter system failure (P(system)) in Fig. 12 can be expressed as follow;

$$\mathrm{P(system)} = \mathrm{P}(A_I)\cdot\mathrm{P}(B_I) + \mathrm{P}(A_I)\cdot\mathrm{P}(C_I) + \mathrm{P}(B_I)\cdot\mathrm{P}(C_I) + \mathrm{P}(C_{AB}) + \mathrm{P}(C_{AC}) + \mathrm{P}(C_{BC}) + \mathrm{P}(C_{ABC})$$

Generally, in reliability analysis, it is assumed that the probabilities of similar events involving similar types of components are the same. According to this assumption, following equations are introduced;

$$\mathrm{P}(A_I) = \mathrm{P}(B_I) = \mathrm{P}(C_I) = Q_1$$

$$\mathrm{P}(C_{AB}) = \mathrm{P}(C_{AC}) = \mathrm{P}(C_{BC}) = Q_2$$

$$\mathrm{P}(C_{ABC}) = Q_3$$

here, the symmetry assumption is applied, so the probability of failure of any given basic event does not depend on the specific components in that basic event. For the basic events corresponding to a CCF group of *m* components, Q_k is defined as;

$$Q_k = probability\ of\ a\ basic\ event\ involving\ k\ specific\ components \quad (1 \le k \le m)$$

Then, the system failure probability (P(system)) can be written as;

$$Q_s = 3Q_1^2 + 3Q_2 + Q_3$$

This Q_k values are also used to calculate the total probability of failure for one component. For instance, the total failure probability of transmitter A can be expressed as follow;

$$Q_t = Q_1 + 2Q_2 + Q_3$$

---

[7] It ignores the possibility that two or more rare evens can occur simultaneously [41]. By using this assumption, the unavailability associated with OR gate is calculated the sum of the unavailability for each input to the OR gate.

In general, the total failure probability of a component in a common cause group of *m* components is

$$Q_t = \sum_{k=1}^{m} \binom{m-1}{k-1} Q_k$$

where, $\binom{m-1}{k-1} = \frac{(m-1)!}{(m-k)!(k-1)!}$, this represents the number of different ways that a specific component can fail with *(k-1)* other components in a group of *m* similar components.

In the Basic Parameter model, Q_k can be calculated from data, so further probabilistic modelling is not necessary, namely there is no extra parameters (β in Beta factor model, α in Alpha factor model, etc.) which we need to estimate. However, the required data to calculate Q_k is usually not available. Therefore, other models have been developed to support this limitation.

According to the selected CCF parametric model, Q_k can be calculated different way that is summarized in Table 1.

Table 1: CCF quantification according to the CCF parametric model [40]

Model	parameters	General form for multiple component failure frequency*
Basic parameter	$Q_1, Q_2, \dots, Q_m$	$Q_k \quad (k = 1, 2, \dots, m)$
Beta factor	Q_t, β	$Q_k = \begin{cases} (1-\beta)Q_t\,, & k = 1 \\ 0\,, & m > k > 1 \\ \beta Q_t\,, & k = m \end{cases}$
Multiple Greek letter	$Q_t, \beta, \gamma, \delta,$ $\dots, m-1 parameters$	$Q_k = \frac{1}{\binom{m-1}{k-1}} \left(\prod_{i=1}^{k} \rho_i \right) (1-\rho_{k+1}) Q_t$ $(\rho_1 = 1, \rho_2 = \beta, \rho_3 = \gamma, \dots, \rho_{m+1} = 0)$
Alpha factor	$Q_t, \alpha_1, \alpha_2, \dots, \alpha_m$	$Q_k = \frac{k}{\binom{m-1}{k-1}} \frac{\alpha_k}{\alpha_t} Q_t \quad (k = 1, \dots, m)$ $\alpha_t \equiv \sum_{k=1}^{m} k\alpha_k$

*Formulas are presented for the basic events in a common cause component group of size *m*.

2.5 CCF parametric model

As explored in above section 2.3, we can select appropriate CCF parametric model based on the properties of the CCF events (definition of CCF and causes of CCF) and available data from operating experience.

According to the parameter estimation approach, the CCF model can be categorized in the direct and indirect model, and shock and non-shock model [9]. Many CCF models have been developed to quantify the CCF events, and O'Connor and Mosleh [42] categorize popular quantitative CCF probability estimation models as basic parameter model, ratio models (e.g., Beta Factor, Alpha Factor and Multiple Greek Letter) and shock models. Classification of CCF parametric model is shown in Figure 13.

In the basic parameter model, probability of basic events is needed to calculate system failure probability. Ideally, the CCF basic event probability can be calculated from data (i.e. counting failures). However, in most cases, we will not be able to find high quality input data because of the rarity of CCF events [43]. In addition, common cause data analysis is often a very subjective process because the available date are generally sparse [44]. Therefore, there are many studies about that how can we utilize incomplete data, and LE DUY and VASSEUR [45] propose an approach for estimation of CCF parameters in case of incomplete data.

The ratio models have been developed to compensate the defect that is caused by incomplete data [9]. The ratio models are widely used in the nuclear and oil & gas industry, and the representative ratio models are Beata Factor Model, Multiple Greek Letter Model, and Alpha Factor Model.

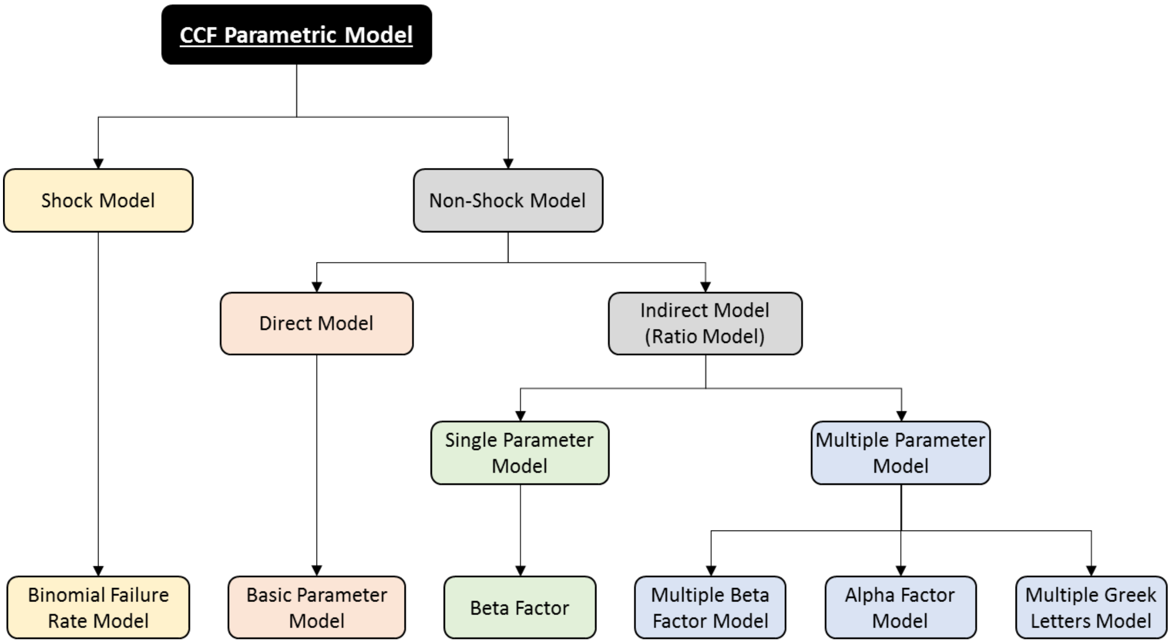

Figure 13: Classification of CCF parametric models

Beta Factor model is most widely used model for the quantification of CCFBEs due to its simplicity [1]. This simplicity arises from an assumption that CCFs always affect all components in the CCF group. Beta Factor model will be introduced in detail in section 2.6.

The MGL model was first introduced by Fleming and Kalinowski [46], and the MGL model is an extension of the Beta Factor model. To overcome the limitation of the Beta Factor model, it takes into account CCF events of different multiplicities. For an m redundant system of identical components, the MGL model uses a number of (m-1) parameters represented by the Greek letters (β, γ, δ, ….), Those parameters describe the conditional probabilities of a double, triple, quadruple… failure given that a failure has occurred.

The Multiple Greek Letter and Alpha Factor model are more accurate because it allows different end states. This is well explained in [47]. There are many possible failure scenarios for a large number of redundant components. Therefore, there are different end states depending on the failure criteria, and these end states have a different effect on the risk assessment. For instance, when a failure occurs, the multiplicity of the failure event can be one or n. In the Beta Factor model, intermediate values of the multiplicity are not allowed. So, depending on the failure criteria, CCF effects on the risk assessment can be overestimated or underestimated. In Multiple Greek letter and Alpha Factor model, the multiplicity of failure can be taken into account to improve accuracy.

The main difference between α in the Alpha Factor model and the parameters of the Multiple Greek letter and Beta Factor model is that the former is a fraction of the events that occur within a system, whereas the latter are fractions of component failure rates [9].

Although each of the models has different parameters, all of them share the same general idea. Component failure probability can be separated into two parts: a dependent section and an independent section. The relation between these two sections is determined with different parameters defined within the specific parametric model selected [48].

2.6 Beta-factor model

The beta-factor model was introduced by Fleming [20], and it is the most commonly used CCF model. The parameter β is the relative proportion of CCFs among all failures of a channel. Consider a system of n identical channels each with constant failure rate λ. Then the system will have a CCF rate $\lambda_C = \beta\lambda$, and each channel has a rate of independent failures $\lambda_I = (1 - \beta)\lambda$. So, the total failure rate of a channel may be written as [1];

$$\lambda = \lambda_I + \lambda_C$$

and the parameter β may be expressed as;

$$\beta = \frac{\lambda_C}{\lambda_I + \lambda_C} = \frac{\lambda_C}{\lambda}$$

When applying the beta factor model, we need to know the total failure rate of the component and corresponding β to analyse the CCFs. Estimating of the β could be challenging work when the available data is incomplete. Two scenarios are to be considered in the approach for determining β: (1) the estimation of beta value is based on data and (2) the estimation is based on check list. In addition, a recent study by SINTEF [49] suggests a combined approach (based on data and check list) to obtain more accurate β in oil and gas industry.

2.7 PDS method

PDS method is developed to quantify the safety unavailability and loss of production for safety instrumented systems (SISs) by SINTEF with industries. In the PDS method, the modelling of CCFs is discussed. To distinguish system configurations, they use an extended version of the Beta Factor model [15]. In order to reflect the system configurations, the PDS model introduces the configuration factor C_{MooN}. The C_{MooN} factor is proposed based on expert judgements supported by some data related to the effect of adding redundancy to a system. For a MooN system, an extended version of the Beta Factor model is suggested as follow [15];

$$\beta_{MooN} = \beta \cdot C_{MooN} \qquad (M < N)$$

C_{MooN}: a modification factor for various voting configurations

β: the factor which applies for a 1oo2 voting

This β is different to β in the standard beta factor model. In the standard beta factor model, β is the conditional probability that a failure of a channel is a CCF. In the PDS method, β is the conditional probability of exactly one extra failure when we know that one channel has failed [1]. Therefore, for a 1oo2 system, β in the standard Beta Factor model is same as β in the PDS method, but for other systems, they have different value.

General formulas for the C_{MooN} factor are provided in [15], and listed in Table 2. This C_{MooN} factor values are based on some empiric results from [50], and this reference suggests the following [15];

- Given a failure of two redundant components, the likelihood of having a simultaneous failure of a third added component may sometimes be as high as 0.5.
- When introducing more and more redundant components it appears that the effect of added redundancy decreases as the number of components increases.
- For systems where the number *N* of parallel components are high (say more than 7-8 components) the likelihood of having *N* simultaneous failures seem to be higher than having exactly *N-1* (or *N-2*, etc. depending on the magnitude of *N*) components failing.

In addition, C_{MooN} factors were based on the following assumptions [15];

- Given a common cause failure of two redundant components, then the probability of a third similar component also to fail due to the same cause will be 50%.
- To cater for the effect of added redundancy decreasing as N increases, it was assumed that:
  - When 3 components are known to have failed, then the probability of a fourth component also failing will be 60%
  - When going from 4 to 5 components then the probability of the fifth component also failing will be 70%, etc.
  - Finally, if 7 components are known to ne failed in a CCF, then the likelihood of the other components also failing is 100% (for any $N \geq 8$)

With these assumptions, sometimes negative values of C_{MooN} are obtained. To make valid C_{MooN} factor for all MooN system, two different "mechanisms" causing a CCF (lethal shock and non-lethal shock) are assumed, detailed explanation is presented in Appendix B of [15].

Table 2: C_{MooN} factors for different voting logics [15]

M/N	N=2	N=3	N=4	N=5	N=6
M=1	$C_{1oo2} = 1.0$	$C_{1oo3} = 0.5$	$C_{1oo4} = 0.3$	$C_{1oo5} = 0.2$	$C_{1oo6} = 0.15$
M=2		$C_{2oo3} = 2.0$	$C_{2oo4} = 1.1$	$C_{2oo5} = 0.8$	$C_{2oo6} = 0.6$
M=3			$C_{3oo4} = 2.8$	$C_{3oo5} = 1.6$	$C_{3oo6} = 1.2$
M=4				$C_{4oo5} = 3.6$	$C_{4oo6} = 1.9$
M=5					$C_{5oo6} = 4.5$

For instance, A circle represents "component A has failed" for a triplicate set of components, and B and C circle are in the same manner (Fig. 14). With the PDS method, it is assumed that if A and B have failed due to a CCF, component C may also fail, but only in 50% of the cases. Therefore, the C_{2oo3} factor is 2 because the fraction of failures affecting 2 or 3 components is

$$0.5 \cdot \beta + 0.5 \cdot \beta + 0.5 \cdot \beta + 0.5 \cdot \beta = 2 \cdot \beta$$

, and the C_{1oo3} is 0.5.

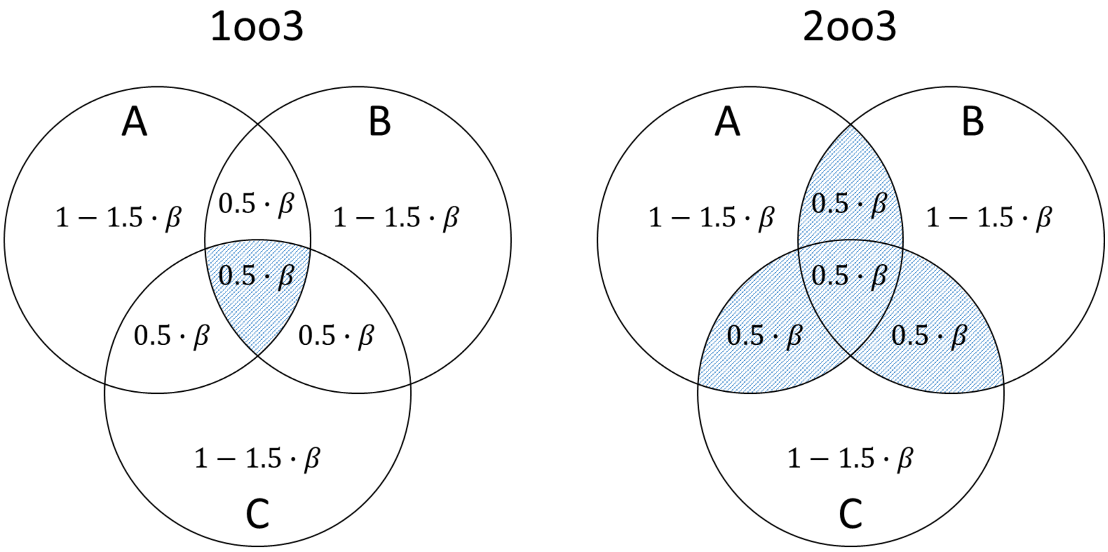

Figure 14: C_{MooN} for 1oo3 and 2oo3 configuration

In addition, the difference between other parametric models (Beta Factor, Alpha Factor, Multiple Greek letter, etc.) and the PDS method is that the PDS method includes check-list to reflect plant specific properties into the estimation of the parameter.

In the CCF parametric models, the parameters are quantified through statistical analysis. In this statistical analysis, the considerable uncertainty is unavoidable because CCF events are relatively complex and rare events [51]. To overcome this drawback, the parameter (β) in the PDS method is estimated based on the operational data and check-list which reflects the plant specific characteristic. A detailed procedure is described in Chap 3.

Chapter 3

CCF parameter estimation

There are two motivations for estimation of beta in the CCF parametric model; i) to produce a generic beta-factor to use in future reliability studies and as input to updating data handbooks, and ii) update values of beta at a specific plant, using plant-specific experience. In this chapter, we will focus on the estimated β, namely how to estimate β in the standard Beta Factor model and PDS method. In addition, what is the limitation of estimated β.

3.1 NUREG Estimators

A commonly used estimators for β could be referred from NUREG/CR-4780 [9].

$\beta_{\widehat{NUREG\_1}}$ in NUREG/CR-4780 [9] is as follow;

$$\beta_{\widehat{NUREG\_1}} = \frac{N_{DU,CCF}}{N_{DU}}$$

N_{DU}: the total number of DU failures experienced for a homogenous population of components observed over a specified period.

$N_{DU,CCF}$: the total number of DU failures included in all CCF events having occurred in the same period

For example, we observed 10 DU failures, and 4 of them are occurred due to a CCF event (Fig. 15). Then, $\widehat{\beta_{NUEG\_1}}$ is as follow;

$$\widehat{\beta_{NUREG\_1}} = \frac{N_{DU,CCF}}{N_{DU}} = \frac{4}{10} = 0.4$$

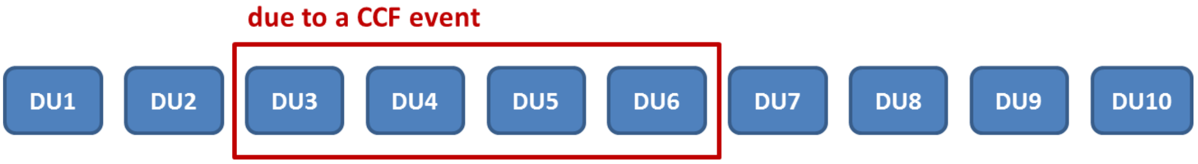

Figure 15: An example of the CCF event

This estimator is often give conservative results (high value) because the number of CCF events are not considered [7]. For instance, for 1oo2 system, if we observe 2 single failures and 1 CCF failure (two components are failed). Then the β is estimated to equal 50%, even if only one third of the events are a CCF event. The NUREG report [9] suggest therefore an alternative estimator as;

$$\widehat{\beta_{NUREG\_2}} = \frac{2 \cdot N_{CCF}}{N_{DU,\,I} + 2 \cdot N_{CCF}}$$

N_{CCF}: the number of observed CCF events

$N_{DU,\,I}$: the number of independent DU failures

With the example in Fig. 15, $\widehat{\beta_{NUREG\_2}}$ is;

$$\widehat{\beta_{NUREG\_2}} = \frac{2 \cdot N_{CCF}}{N_{DU,\,I} + 2 \cdot N_{CCF}} = \frac{2\times 1}{6 + 2\times 1} = \frac{2}{8} = 0.25$$

We could see that the value of $\widehat{\beta_{NUREG\_2}}$ is lower than $\widehat{\beta_{NUREG\_1}}$. Hauge, et al. [26] state as follow; $\widehat{\beta_{NUREG\_2}}$ may be considered non-conservative since all CCF events that include more than two failures are only counted as double failures.

3.2 Challenges of the NUREG estimators

Estimation of the β is problematic due to the assumption of the standard beta-factor model which is all components of a CCF group will fail when a CCF event occurs. In this connection, the NUREG estimators have some limitations, for example, these two estimators cannot reflect the configuration of components. Therefore, the same β is obtained for a 2oo4 and 3oo4 system (Fig. 16).

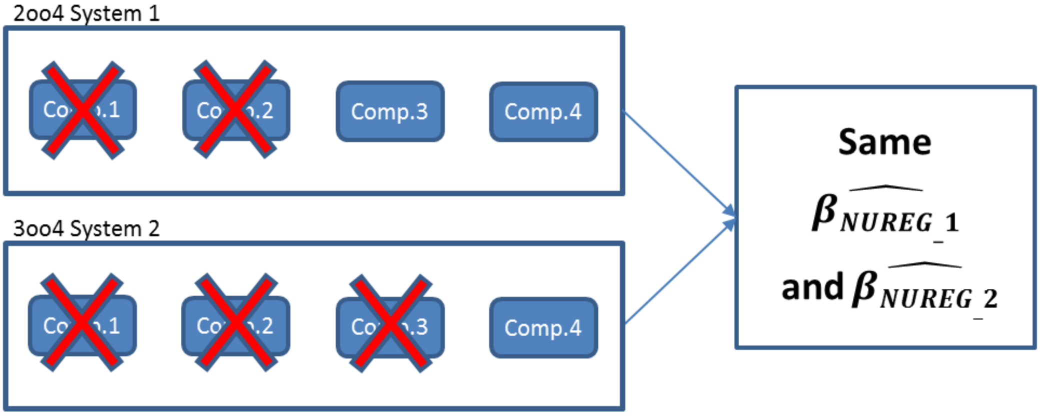

Figure 16: Challenge of the NUREG estimators

3.3 Extended Beta Factor model in PDS method

To overcome the limitation of NUREG estimators, new generic beta-factor was suggested in the PDS method. In the standard beta-factor model, a CCF is assumed to affect all the redundant components. In the PDS method, modification factors (C_{moon}-factor) are introduced to allow any number of components to fail in a CCF of any voting configuration.

In section 2.7, the different meaning of β in the standard beta factor model and β in the PDS method is presented. As a result of this alternative definition of β, CCFs are implemented in the reliability measure in different way (Fig. 17).

For instance, consider 1oo2, 1oo3, and 2oo3 voted group of identical channels with DU failure rate λ_{DU}. The group is exposed to CCFs that are modelled by the Beta Factor model, and is proof-tested with proof test internal τ and the proof tests are assumed to be perfect. The PFD_{avg}[8] of these MooN system is determined as a sum of the individual failure part and failures due to CCFs ($\beta \frac{\lambda_{DU}\tau}{2}$).

$$PFD_{avg} \approx PFD^{I} + PFD^{CCF} = PFD^{I} + \beta \frac{\lambda_{DU}\tau}{2}$$

According to the system configuration, the individual parts are selected, and the CCF part is the same for all configuration in the Beta Factor model. In this wise, the Beta Factor model cannot reflect the system configuration.

In the PDS method, the CCF part (PFD^{CCF}) of the average probability of failure on demand is $\beta \cdot C_{MooN} \cdot \frac{\lambda_{DU}\tau}{2}$, and the system configurations are reflected by the modification factor (C_{MooN}). In addition, this β is different from the standard beta factor model as previously stated. For this reason, Hauge, et al. [26] suggest new generic β value based on operational failure reviews for selected equipment groups. Furthermore, to reflect the site-specific condition to the β, they suggest a combination of generic beta values from operational database and equipment specific checklists. The process is straightforward. Firstly, generic beta values are determined from database, using $\beta_{\widehat{NUREG\_1}}$, $\beta_{\widehat{NUREG\_2}}$ and $\widehat{\beta_{PDS}}$. Secondly, modification factors of check-lists are obtained by equipment specific checklists, using weight and efficiency of each CCF category. Finally, we can get updated plant specific beta values from the product of generic beta factor and modification factor (Fig. 18).

In addition, check-list approach is used to determine the generic beta, and correction factors to modify the beta-factor for different MooN configurations is proposed in IEC 61508-6 [21]. This approach is similar to the PDS method, but it is only based on the checklists and expert-judgement.

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[8] PFD_{avg} is the average probability of failure on demand as one of reliability measures [14].

In this thesis, we will focus on the estimation of the PDS estimator ($\widehat{\beta_{PDS}}$).

- **Standard Beta Factor Model**

$$PDF_{1oo2}^{CCF} = PDF_{1oo3}^{CCF} = PDF_{2oo3}^{CCF} = \ ... = \ \beta \cdot \frac{\lambda_{DU} \cdot \tau}{2}$$

- **PDS Method**

$$PDF_{MooN}^{CCF} = \beta_{Moon} \cdot \frac{\lambda_{DU} \cdot \tau}{2}$$

$$\downarrow$$

$$\beta_{Moon} = C_{Moon} \cdot \beta$$

$$\downarrow$$

$$\beta = \beta_{generic} \cdot Modification\ factor\ (Checklist)$$

$$\downarrow$$

$$\beta_{generic}\ is\ derived\ from\ \widehat{\beta_{NUREG\_1}},\ \widehat{\beta_{NUREG\_2}}\ \text{and}\ \widehat{\beta_{PDS}}$$

Figure 17: The difference meaning of beta in the standard beta factor model and the PDS method

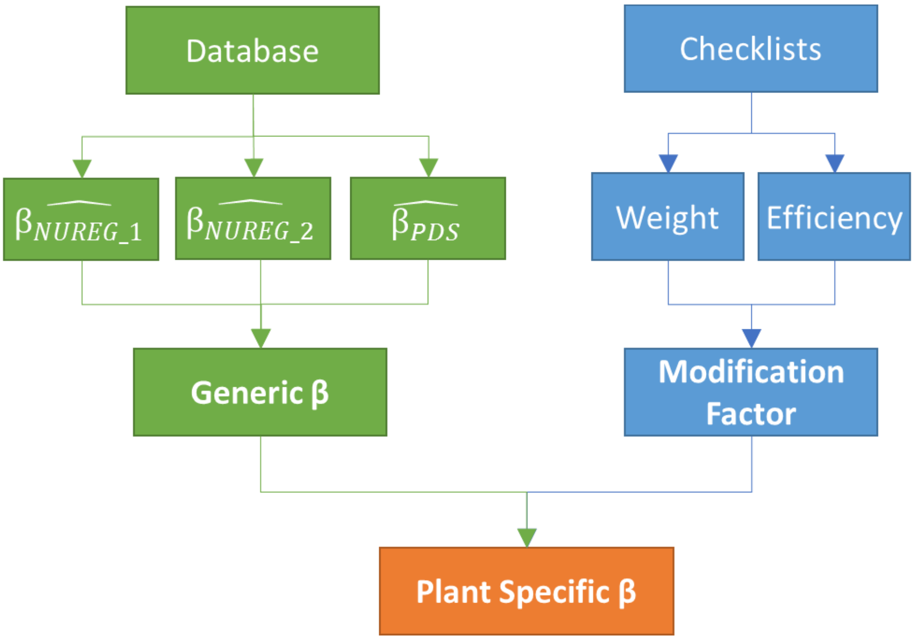
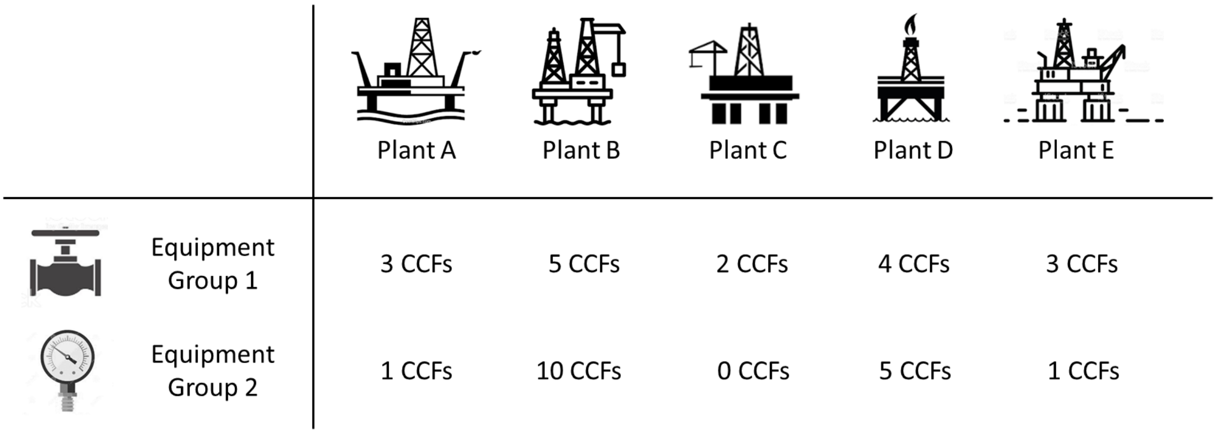


Figure 18: The procedure to obtain plant specific beta in the PDS method

One of challenges of PDS method is to determine modification factors from checklists; more specifically, to determine efficiency of each CCF defence. In the PDS method, the efficiencies are uniformly assumed for every type of equipment, from 3 to 0.1. However, the efficiencies may significantly vary between equipment. As stated in the SINTEF report, on some installations no CCF events have been observed for certain equipment groups, whereas on other installations a very high frequency of CCFs has been observed for certain equipment [49]. For instance, let us say that we have two equipment groups in five plants as shown in Figure 19.



	Plant A	Plant B	Plant C	Plant D	Plant E
Equipment Group 1	3 CCFs	5 CCFs	2 CCFs	4 CCFs	3 CCFs
Equipment Group 2	1 CCFs	10 CCFs	0 CCFs	5 CCFs	1 CCFs

Figure 19: An example of two equipment groups and CCFs

There is no significant difference between the numbers of CCFs in equipment group 1, whereas there is a large difference between CCFs in equipment group 2. This may mean that the efficiency of defence for equipment group 1 is lower than the efficiency of defence for equipment group 2. Therefore, efficiencies of defences need to be adjusted for each equipment group.

One solution of this challenge could be to adjust efficiencies based on the distribution of CCFs. From the above example, the average number of CCFs of the two equipment groups are equally 3.4, but the standard deviations are different. The standard deviation of equipment group 1 is 1.14, whereas the standard deviation of equipment group 2 is 4.16. We may use this value to adjust the efficiency.

3.4 How to get PDS estimator

To get the PDS estimator ($\widehat{\beta_{PDS}}$), Hokstad [52] introduced the multiple beta factor(MBF) model which distinguishes between different system configurations. In the MBF model, the probability Q_{koon} is the probability that a system with *n* identical channels has a failure with multiplicity *k*, for *k* = 1, 2, 3….*n* [1];

$$Q_{koon} = C_{koon} \cdot \beta Q$$

Q: the probability that a channel is in a failed state

β: the conditional probability of exactly one extra failure when we know that one channel has failed

C_{koon}: a factor that depends on the configuration of the system

The MBF model considers the multiplicity of the failure which is the number of simultaneously failed components. We can therefore calculate the probability of exactly *j* of the *n* channels being in a failed state as follow;

$$f_{j:n} = \binom{n}{j} g_{j,n} \tag{1}$$

$g_{j,n}$: the probability that exactly *j* specified channels have failed out of *n* channels due to a CCF

The probability of CCF for a *koon* configuration is

$$Q_{koon} = \sum_{j=n-k+1}^{n} f_{j:n} \tag{2}$$

By introducing $G_{j,n} = \frac{g_{j,n}}{\beta Q}$ [52]

$$G_{j,n} = \frac{g_{j,n}}{\beta Q} = \sum_{i=0}^{n-j} (-1)^i \binom{n-j}{i} \prod_{l=2}^{j-1+i} \beta_l\,, \quad j = 2, 3, \dots, n \tag{3}$$

and the modification factor is;

$$C_{koon} = \sum_{j=n-k+1}^{n} \binom{n}{j} G_{j,n}, \ for\ k = 1, 2, \dots, n-1 \tag{4}$$

In the MBF model, by increasing the number of channels from n to $n+1$, we have to introduce a new parameter β_p ($p = 2, 3, \ldots, n-1$) which is the probability that a specific channel fails in a CCF, given that p specified channels are known to fail in this CCF event.

In most cases, however, we do not have the information available to perform separate estimation of all relevant β_p, and some simplification of the model is appropriate [52]. Hokstad [52] and Hokstad, et al. [53] derived the maximum likelihood estimate (MLE) for β_p.

If we assume that the failure data was collected for systems with the same number of components in the CCF group, the MLE for β_p based on failure data of a system with n channels is [7];

$$\hat{\beta}_{p,n} = \frac{p+1}{n-p} \frac{\sum_{j=p+1}^{n} \binom{j}{p+1} \cdot X_{j,n}}{\sum_{j=p}^{n} \binom{j}{p} \cdot X_{j,n}} \tag{5}$$

$X_{j,n}$: number of failure events resulting in exactly j channels failing, $j = 1, 2, \ldots, n$

In this thesis, fixed number of channels is only considered, estimators for the β_p using data with different number of channels are explained in [53].

To prove eq. (5), Hokstad [52] let $p_{j,n}$ be the conditional probability of having exactly j failed channels, given that at least one of them have failed. Letting $X_n = \sum_j X_{j,n}$ be the total number of failure events, then it is well-known that the Maximum Likelihood Estimator (MLE) for $p_{j,n}$ equals $\hat{p}_{j,n} = \frac{X_{j,n}}{X_n}$ for $j = 1, 2, \ldots, n$ based on these observations.

Using eq. (1), $p_{j,n}$ is transferred to $p_{j,n} = \frac{f_{j,n}}{\sum_{i=1}^{n} f_{i,n}}$. This gives the MLE for the $f_{j,n}$, and the eq. (5) follow from the relation between eq. (1) and (3). Detailed procedure is not fully understood, but this thesis accepts all principles from [52] and [53], including eq. (5).

Hauge, et al. [54] propose the following parameters to simplify the eq. (5).

$n = the\ size\ of\ the\ CCF\ group\ affected\ by\ failure\ event$

$K = Number\ of\ failure\ events$ (Independent Failure + Common Cause Failure)

$Y_j = Number\ of\ failed\ components\ of\ failure\ event\ j,\ (j = 1,\ 2,\ \ldots.,\ K)$

Then, $\hat{\beta}_{p,n}$ is simplified as follow;

$$\widehat{\beta_{MLE,K}} = \frac{\sum_{j=1}^{K} Y_j(Y_j-1)}{(n-1)\sum_{j=1}^{K} Y_j} = \widehat{\beta_{PDS}} \tag{6}$$

The transition procedure from eq. (5) to eq. (6) is not explained in [26] and [54]. So, it is not so easy to understand, but this thesis accepts this transition without verification.

Chapter 4

Challenges and Improvement of the PDS estimator

4.1 Challenges of the PDS estimator

To estimate $\widehat{\beta_{PDS}}$, we need to obtain values of relevant parameters; n (CCF group size[9]), K (Number of failure events), and Y_j (Number of failed components for failure even j). The values of K and Y_j can be easily obtained from operational data, but defining the size of the CCF group (n value) is somewhat more challenging due to how the data has been registered and collected [54].

For instance, components (e. g. transmitters, valves, sensors etc.) can be installed in 1oo2 or 2oo4 configuration or any others configuration, but this information has not been clearly registered in collected data. To support this uncertainty, two assumptions about the size of CCF group are suggested in the PDS method;

1. The size of CCF group (n_j) equals to the CCF event with most failures
2. All n_j have same value

This thesis focuses on the first assumption ($n_j = the\ CCF\ event\ with\ most\ fairlues$). For instance, let us say that we have observed several CCF events with maximum five component failures in the entire database. Then, the CCF group size is assumed to five, even though the actual CCF group size could be larger than five. Like this, the CCF group size could be assumed to 3, 4, 5, …, n according to the observed maximum failures.

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[9] Hauge, et al. [7] define a CCF group as a collection of identical/similar components for which a CCF event can be registered.

We can find a good example in the SINTEF report [49] which describes the parameters (n_j, K, Y_j) and the assumptions.

- SINTEF example

  There are 41 single DU failure events and 3 CCF events with 9, 2 and 2 DU failures respectively (Fig. 20). The number of failure events K is 44 (41+3), with the CCF group size $n_1 = n_2 = \cdots = n_{44} = 9$, and the number of components $Y_1 = Y_2 = \cdots = Y_{41} = 1$, $Y_{42} = 9$ and $Y_{43} = Y_{44} = 2$. With these parameters, $\widehat{\beta_{PDS}}$ can be obtained as;

$$\widehat{\beta_{PDS}} = \frac{41 \cdot 1 \cdot 0 + 9 \cdot 8 + 2 \cdot 1 + 2 \cdot 1}{8 \cdot (41 \cdot 1 + 9 + 2 + 2)} = 0.1759$$

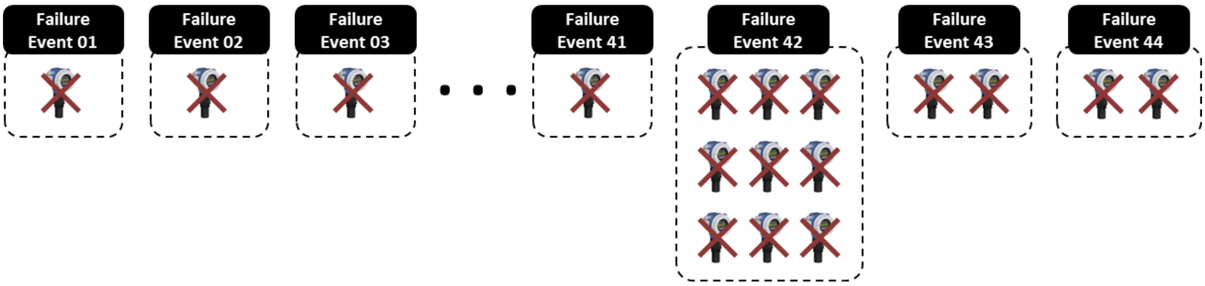


Figure 20: Example of observed failure events from SINTEF report

As we can see from above SINTEF example, the CCF group size is assumed to nine (most failures with the CCF event). Because estimating the $\widehat{\beta_{PDS}}$ of the SINTEF method is sensitive to the CCF group size [7], it is worth noticing that to investigate whether this assumption is reasonable or not. Generally, the probability to observe nine failures by a single CCF event seems to be extremely low when an actual group size is nine, then the actual CCF group size could be greater than nine.

In SINTEF example, the assumption of the CCF group size can be correct, only when we observe nine component failures by a CCF event, and this probability is expected to be extremely low. To calculate the probability of this assumption, multiple beta factor model is used which is discussed in section 3.4.

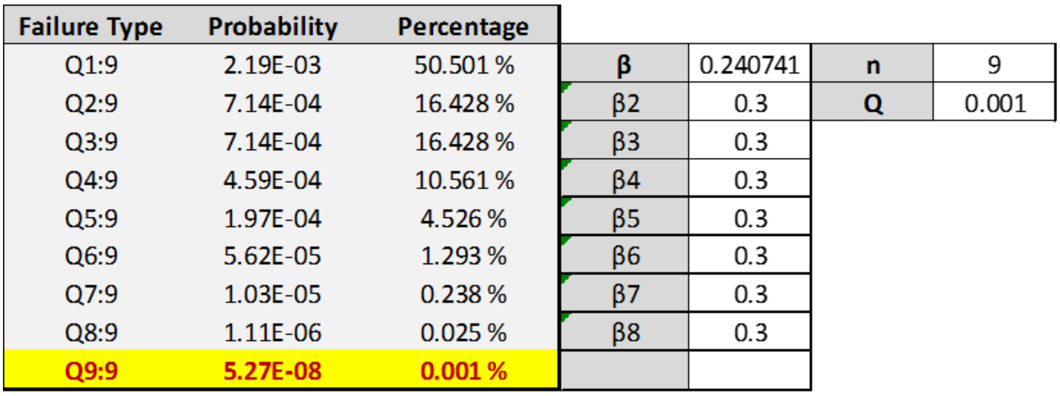
$$Q_{koon} = C_{koon} \cdot \beta Q$$

Q_{koon} is the probability that the *koon* system is in a failed state. Other assumptions are as follows;

- $\beta_p = 0.3\ (p \geq 2)$

  As mentioned above (3.1), estimation of β_p is needed and the importance of the β_p value are explained in [52] and [53]. Here, 0.3 is used.
- $\mathrm{Q} = 0.001$
- $\beta = \frac{9+2+2}{41+9+2+2} \approx 0.2407(\widehat{\beta_{NUREG_1}})$

With above assumptions and input data, following probabilities are calculated: one component is in a failed state (Q1:9), two components are in a failed state due to a CCF (Q2:9), …, and nine components are in a failed state due to a CCF (Q9:9). The results and a percentage of these probabilities are listed in Fig. 21.



Failure Type	Probability	Percentage
Q1:9	2.19E-03	50.501 %
Q2:9	7.14E-04	16.428 %
Q3:9	7.14E-04	16.428 %
Q4:9	4.59E-04	10.561 %
Q5:9	1.97E-04	4.526 %
Q6:9	5.62E-05	1.293 %
Q7:9	1.03E-05	0.238 %
Q8:9	1.11E-06	0.025 %
Q9:9	**5.27E-08**	**0.001 %**

β	0.240741
β2	0.3
β3	0.3
β4	0.3
β5	0.3
β6	0.3
β7	0.3
β8	0.3

n	9
Q	0.001

Figure 21: The probability of that we observe 9 component failures by a CCF event

The "percentage" of *p* component failure is the ratio of the probability of *p* component failure to the probability of all kinds of failures.

$$Percentage\ of\ p\ component\ failure = \frac{Qp:9}{\sum_{j=1}^{9} Qj:9}$$

When we observe a failure, the failure can be an individual failure with 50.501% probability, and the failure can be nine component failure by a CCF with 0.001% probability. Therefore, the probability that the assumption is correct is extremely low (0.001%). With this result, we could say that the size of the CCF event with most failures can be lower than actual CCF group size with very high probability.

4.2 Improved approach to estimate the CCF group size

As we observed above, the size of the CCF event with most failures can be lower than actual CCF group size with very high probability. To estimate the actual CCF group size, this thesis suggests to use the most common event (individual failure) as a criterion to estimate the CCF group size. An Individual Failure Ratio (IFR) is introduced as follow;

$$\mathrm{IFR} = \frac{Number\ of\ individual\ failures}{\sum_{j=1}^{K} Y_j} = \frac{Q1\colon n}{\sum_{j=1}^{K} Qj\colon n}$$

We may say that this Individual Failure Ratio (IFR) is equal to the percentage of one component failure.

For instance, in the SINTEF example (Fig. 20), the IFR is 41/54 = 0.7593 = 75.93%. If we adopt the assumption of the PDS method, then the CCF group size is 9, and the IFR is 50.501% (Fig. 21). The CCF group size needs to be adjusted to make the ratio from 50.501% to 75.93% (Table 3). The IFR become 76.1% when the CCF group size is 43. There is considerable difference in the estimated CCF group size, and this can lead to significant effect on $\widehat{\beta_{PDS}}$.

In this section, it is assessed that how $\widehat{\beta_{PDS}}$ is affected by the different CCF group size, and the new approach to estimate CCF group size (IFR approach) is suggested. The $\widehat{\beta_{PDS}}$ with 9 CCF group size is about 5.25 times larger than the $\widehat{\beta_{PDS}}$ with 43 CCF group size. Therefore, we may conclude that $\widehat{\beta_{PDS}}$ could be overestimated with the assumption that *"maximum number of failure components equals to the CCF group size"*, at least for the case of this SINTEF example. To obtain more realistic $\widehat{\beta_{PDS}}$ value, the CCF group size could be estimated with IFR approach.

Table 3: Individual failure ratio of CCF group sizes (*n = 2, 3, …, 80*) for the SINTEF example

n	Individual Failure Ratio (IFR)	n	Individual Failure Ratio (IFR)
		41	75.2 %
2	86.3 %	42	75.6 %
3	75.4 %	43	76.1 %
4	67.0 %	44	76.5 %
5	60.7 %	45	76.9 %
6	56.3 %	46	77.3 %
7	53.3 %	47	77.6 %
8	51.4 %	48	78.0 %
9	50.5 %	49	78.3 %
10	50.3 %	50	78.7 %
11	50.5 %	51	79.0 %
12	51.1 %	52	79.3 %
13	52.0 %	53	79.6 %
14	53.0 %	54	80.0 %
15	54.1 %	55	80.2 %
16	55.3 %	56	80.5 %
17	56.5 %	57	80.8 %
18	57.6 %	58	81.1 %
19	58.8 %	59	81.3 %
20	59.9 %	60	81.6 %
21	61.0 %	61	81.8 %
22	62.0 %	62	82.1 %
23	63.0 %	63	82.3 %
24	64.0 %	64	82.5 %
25	64.9 %	65	82.8 %
26	65.8 %	66	83.0 %
27	66.6 %	67	83.2 %
28	67.4 %	68	83.4 %
29	68.2 %	69	83.6 %
30	68.9 %	70	83.8 %
31	69.6 %	71	84.0 %
32	70.3 %	72	84.2 %
33	70.9 %	73	84.4 %
34	71.5 %	74	84.5 %
35	72.1 %	75	84.8 %
36	72.7 %	76	84.8 %
37	73.2 %	77	84.8 %
38	73.7 %	78	85.1 %
39	74.2 %	79	85.2 %
40	74.7 %	80	85.1 %

Table 4: $\widehat{\beta_{PDS}}$ for the two CCF group sizes

CCF group size	$\widehat{\beta_{PDS}}$
9	0.1759
43	0.0335

Chapter 5

Case Study

In Chapter 4, the Individual Failure Ratio (IFR) approach is proposed to estimate more realistic CCF group size. To apply this methodology, a case study is conducted with data from SINTEF report [26]. In this thesis, this data is called ‘SINTEF data’.

Hauge, et al. [26] carried out operational failure reviews of 12,000 maintenance notifications, and they compiled statistics on DU failures, individual DU failures, common cause DU failures and the number of CCF event for each equipment group are listed in Table 5. This SINTEF data is the input data of a case study to demonstrate the IFR approach which is suggested in Chapter 4. Following equipment is excluded because they have very few or no CCF;

1) Deluge valve – only one CCF
2) Line gas detector – only one CCF
3) Heat detector – Only one DU failure, no CCF
4) Temperature transmitter – only three DU failures, no CCF

Blue coloured equipment in Table 5 is included in this case study. In section 5.1, the IFR approach is applied to the ESD/PSD valves, and procedures to obtain new $\widehat{\beta_{PDS}}$ are demonstrated in detail. The new $\widehat{\beta_{PDS}}$ of all the other equipment is obtained with the same procedure, and the results are listed in Appendix D.

Table 5: Input data from operational reviews for each equipment group

Equipment group	N_{DU}	$N_{DU,I}$	N_{CCF}	$N_{DU,CCF}$
ESD/PSD valves (incl. riser ESD valves)	279	211	12	68
Blowdown valves	73	56	4	17
Fire dampers	44	21	6	23
Deluge valves*	5	3	1	2
PSVs	148	116	11	32
Gas detectors (point and line*)	74	54	5	20
Flame detectors	23	15	3	8
Smoke detectors	41	30	5	11
Heat detectors*	1	1	0	0
Level transmitters	54	41	3	13
Pressure transmitters	44	31	4	13
Temperature transmitters*	3	3	0	0
Flow transmitters	11	5	2	6

*This equipment is excluded because there are not enough number of failures

5.1 ESD/PSD valves (include riser ESD valves)

In the SINTEF data, 266 DU failures and 10 CCF events were observed for the shutdown valves. Detailed explanation of the CCF events are described in section 4.3 of [26]. Number of DU CCFs in each CCF event are listed in Table 6.

Table 6: Number of failed components of ESD/PSD valves

	Number of failed components
DU failures	266
CCF events	10*
CCF1	19
CCF2	11
CCF3	6
CCF4	6
CCF5	4
CCF6	3
CCF7	3
CCF8	2
CCF9	2
CCF10	2

*In the SINTEF report, 11 CCF events are observed, but one of them is *"an additional (unknown) number of DU failures (delayed operation) were due to inadequate bleed-off (wrong tuning of bleed-off valve)"*. So, in this case study, this event is excluded to improve the accuracy.

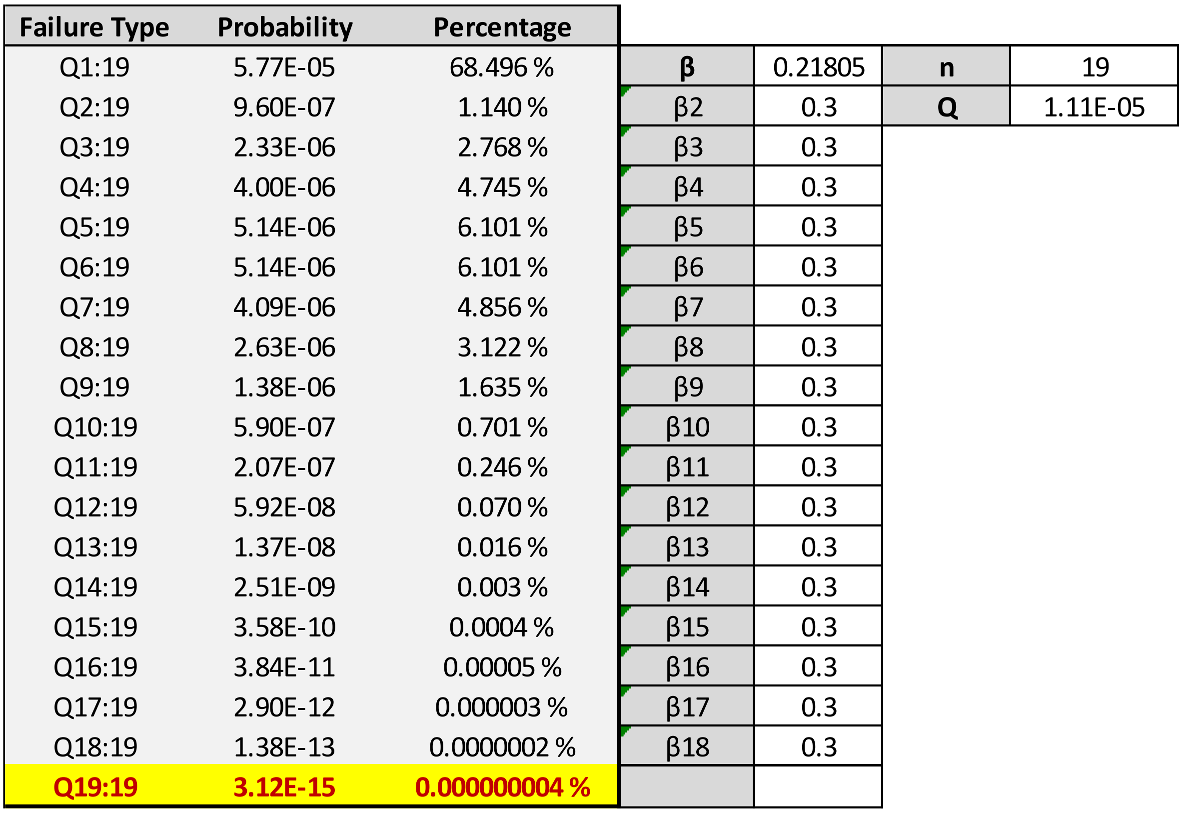
As discussed in section 4.2, the IFR is proposed to estimate the proper CCF group size, the IFR is defined as the ratio of individual component failure to the total number of failures.

$$\text{IFR} = \frac{Number\ of\ individual\ failures}{\sum_{j=1}^{K} Y_j} = \frac{Q1{:}\,n}{\sum_{j=1}^{K} Qj{:}\,n}$$

The IFR of shutdown vales is 208/266 ≈ 0.782.

If we adopt the assumption of the PDS method, the CCF group size equals to the most failures of the CCF events. In this case, the CCF group size of shutdown valves is 19. However, the probability to witness 19 failures from 19 CCF group size is extremely low as shown in Figure

22. In addition, the IFR of shutdown valves with 19 CCF group size is 0.685, which lower than the observed IFR value of 0.782.



Failure Type	Probability	Percentage		
Q1:19	5.77E-05	68.496 %	**β**	0.21805
Q2:19	9.60E-07	1.140 %	β2	0.3
Q3:19	2.33E-06	2.768 %	β3	0.3
Q4:19	4.00E-06	4.745 %	β4	0.3
Q5:19	5.14E-06	6.101 %	β5	0.3
Q6:19	5.14E-06	6.101 %	β6	0.3
Q7:19	4.09E-06	4.856 %	β7	0.3
Q8:19	2.63E-06	3.122 %	β8	0.3
Q9:19	1.38E-06	1.635 %	β9	0.3
Q10:19	5.90E-07	0.701 %	β10	0.3
Q11:19	2.07E-07	0.246 %	β11	0.3
Q12:19	5.92E-08	0.070 %	β12	0.3
Q13:19	1.37E-08	0.016 %	β13	0.3
Q14:19	2.51E-09	0.003 %	β14	0.3
Q15:19	3.58E-10	0.0004 %	β15	0.3
Q16:19	3.84E-11	0.00005 %	β16	0.3
Q17:19	2.90E-12	0.000003 %	β17	0.3
Q18:19	1.38E-13	0.0000002 %	β18	0.3
Q19:19	**3.12E-15**	**0.000000004 %**		

n	19
Q	1.11E-05

Figure 22: The probability of that we observe *n* components failure by a CCF event *(n = 1, 2, …, 19*)

The CCF group size needs to be adjusted to make IFR with 78.2%. As shown in the Table 7, the IFR becomes 78.3%, when the CCF group size is 32.

Figure 23 illustrates how the IFR is influenced by values selected for group size in the rage from 2 to 80. For the correlation between CCF group size and IFR, the graph displays a curve that has minimum value when the CCF group size is around 10 (Fig. 23). For all the equipment with reasonable CCF group size (shutdown valves, blowdown valves, pressure safety valves, and level transmitters), shows similar curve shape, but the trend could not be identified in this case study due to the limited number of equipment groups. Case studies with more data need to be conducted to identify the reason and trend of the shape of this graph.

Table 7: Individual failure ratio of CCF group sizes ($n = 2, 3, \ldots, 80$) for the ESD/PSD valves

n	Individual Failure Ratio (IFR)	n	Individual Failure Ratio (IFR)
		41	82.2 %
2	87.8 %	42	82.6 %
3	78.3 %	43	82.9 %
4	71.2 %	44	83.2 %
5	66.2 %	45	83.5 %
6	62.8 %	46	83.8 %
7	60.7 %	47	84.1 %
8	59.6 %	48	84.4 %
9	59.3 %	49	84.7 %
10	59.5 %	50	84.9 %
11	60.1 %	51	85.2 %
12	60.9 %	52	85.4 %
13	61.9 %	53	85.7 %
14	63.0 %	54	85.9 %
15	64.1 %	55	86.1 %
16	65.2 %	56	86.3 %
17	66.4 %	57	86.5 %
18	67.4 %	58	86.7 %
19	68.5 %	59	86.9 %
20	69.5 %	60	87.1 %
21	70.5 %	61	87.3 %
22	71.4 %	62	87.5 %
23	72.3 %	63	87.7 %
24	73.1 %	64	87.8 %
25	73.9 %	65	88.0 %
26	74.6 %	66	88.2 %
27	75.3 %	67	88.3 %
28	76.0 %	68	88.5 %
29	76.6 %	69	88.6 %
30	77.2 %	70	88.8 %
31	77.8 %	71	88.9 %
32	78.3 %	72	89.0 %
33	78.8 %	73	89.2 %
34	79.3 %	74	89.3 %
35	79.8 %	75	89.4 %
36	80.2 %	76	89.6 %
37	80.7 %	77	89.7 %
38	81.1 %	78	89.8 %
39	81.5 %	79	89.6 %
40	81.9 %	80	89.9 %

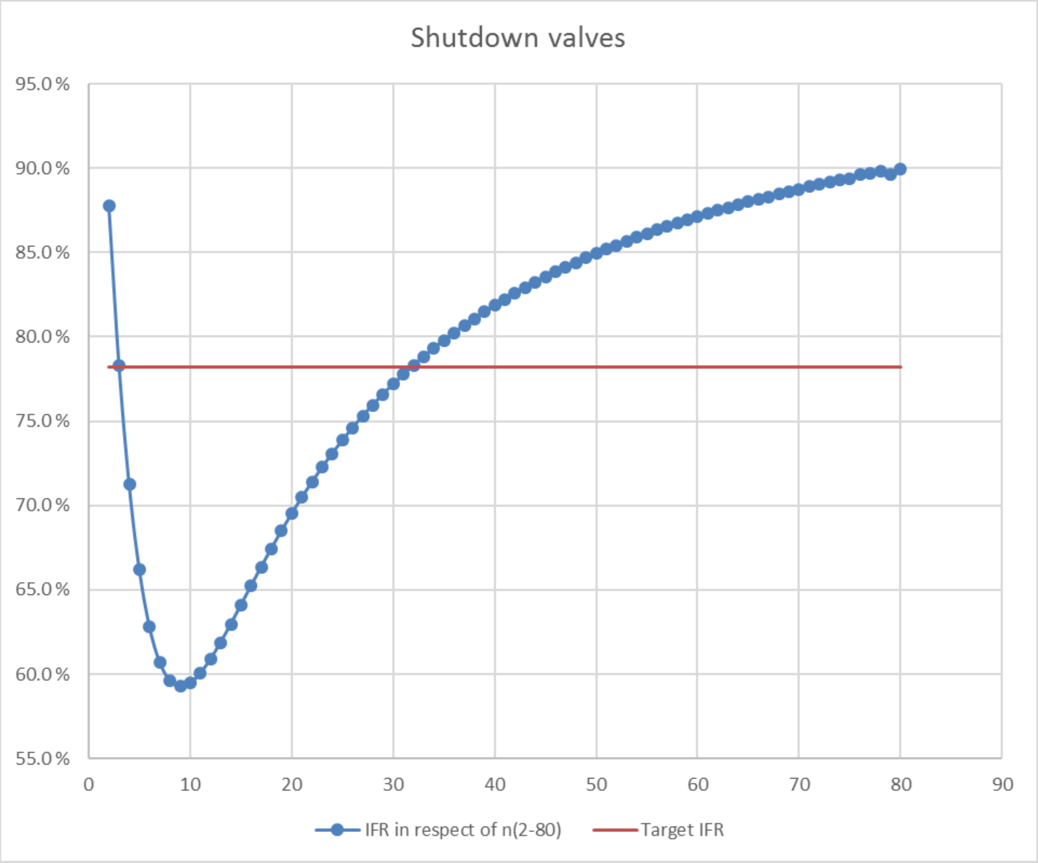


Figure 23: The single failure ratio is influenced by values selected for group size in the rage from 2 to 80

To summarize, the CCF group size with the assumption of the PDS method (old CCF group size) is 19, while the CCF group size with IFR approach (new CCF group size) is 32. The $\widehat{\beta_{PDS}}$ with these two CCF group sizes are calculated in Table 8. The $\widehat{\beta_{PDS}}$ with 19 CCF group size (old $\widehat{\beta_{PDS}}$) is about 1.72 times larger than with 32 CCF group size (new $\widehat{\beta_{PDS}}$).

Table 8: $\widehat{\beta_{PDS}}$ for the two CCF group sizes

	CCF group size	PDS estimator ($\widehat{\beta_{PDS}}$)
Old	19	0.1132
New	32	0.0657

The new $\widehat{\beta_{PDS}}$ of all the other equipment is obtained with the same procedure, and the results are listed in Appendix D.

5.2 Summary and Discussion of Case Study

The results of the case study are listed in Table 9. $\widehat{\beta_{PDS}}$ (old) is calculated with the assumption in the PDS method (The size of CCF group equals the CCF event with most failures). The CCF group size (old) is the CCF event with most failures. $\widehat{\beta_{PDS}}$ (new) and CCF group size (new) are calculated based on newly proposed methodology in section 4.2.

Table 9: Results of the case study

Equipment group	$\widehat{\beta_{NUREG\_1}}$	$\widehat{\beta_{NUREG\_2}}$	$\widehat{\beta_{PDS}}$ (old)	$\widehat{\beta_{PDS}}$ (new)	CCF group size (old)	CCF group size (new)
Shutdown valves	23%	9%	11%	7%	19	32
Blowdown valves	23%	13%	15%	4%	10	38
Fire dampers	52%	36%	37%	N/A	6	N/A
PSVs	22%	16%	11%	2%	6	31
Gas Detectors (Point)	44%	20%	37%	N/A	10	N/A
Flame detectors	35%	29%	23%	N/A	4	7
Smoke detectors	27%	25%	17%	0.46%	3	76
Level transmitters	24%	13%	18%	3%	9	43
Pressure transmitters	30%	21%	19%	N/A	5	7
Flow transmitters	55%	44%	42%	2%	4	N/A

For the shutdown valve, blowdown valve, pressure safety valve, and level transmitter, reasonable CCF group size are obtained. However, new CCF group size cannot be estimated for the fire damper, point gas detector, flame detector, pressure transmitter, and flow transmitter.

For equipment whose new CCF group size cannot be obtained, it is noticed that the value of $\widehat{\beta_{NUREG\_1}}$ is over 0.3. For instance, the $\widehat{\beta_{NUREG\_1}}$ value of the fire damper is 0.52 that seems too large. In the Humphreys' method [55], the beta value is determined between 0.01% and 30%, and the beta value for the SIS is not over the 10% in IEC 61508. In addition to this large $\widehat{\beta_{NUREG\_1}}$ value, relatively small number of DU failures (compare to shutdown, blowdown and pressure safety valves) are observed for those equipment; 1) fire damper: 44 DU, 2) point gas detector: 59 DU, 3) flame detector: 23 DU, 4) pressure transmitter: 44 DU, and 5) flow transmitter: 11 DU.

It can be inferred that not enough data (small number of observed failures) lead to uncertainty in $\widehat{\beta_{NUREG\_1}}$ value[10]. New CCF group size is affected by this uncertain $\widehat{\beta_{NUREG\_1}}$ because $\widehat{\beta_{NUREG\_1}}$ is one of input data to calculate the ratio of the probability of one component failure to the probability of all components failures as stated in section 4.1. Therefore, the new CCF group size could not be obtained for the equipment with the $\widehat{\beta_{NUREG\_1}}$ value over 0.3.

For Shutdown valve (266 DU), blowdown valve (73 DU), pressure safety valve (148 DU), and level transmitter (54 DU), reasonable new CCF group size can be obtained because it has enough number of DU failures compare to the flame detector, flow transmitter, pressure transmitter, etc. In these cases, all of new CCF group sizes are bigger than old CCF group size with existing assumption (the size of CCF group (n_j) equals the CCF event with most failures). As a result of this, the value of new $\widehat{\beta_{PDS}}$ is smaller than old $\widehat{\beta_{PDS}}$ as shown in Table 9.

One exception is smoke detector. For smoke detector, the $\widehat{\beta_{NUREG\_1}}$ value is lower than 0.3 like shutdown valves, blowdown valves, pressure safety valves and level transmitter. However, the obtained new CCF group size is relatively large, and the new $\widehat{\beta_{PDS}}$ is much smaller than the others. Further study need to be conducted with more case studies to investigate the reason of these abnormal values.

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[10] For instance, if someone casts a dice for 10,000 times or more, then the number of each outcome would be evenly distributed. However, if he casts a dice for only six times, then the number of each outcome might not be even. So, he may get six "3" in a row.

For the CCF group size, 31 or 43 seems quite high value because normally number of redundant components are two or three. However, the definition of CCF event in PDS method is not restricted to the events where all the failed components belong to the same safety function [26]. CCF event may therefore go beyond the boundaries of a single function, and the CCF group could include several systems. In this respect, 43 can be a reasonable CCF group size.

Results of this case study are listed in Table 10, with their equations. In all cases, $\widehat{\beta_{NUREG\_1}}$ has the largest value and $\widehat{\beta_{PDS}}$ has lowest value. We may conclude that $\widehat{\beta_{NUREG\_1}}$ is relatively conservative estimator and $\widehat{\beta_{PDS}}$ is less conservative estimator at least in this case study.

Table 10: Comparison of $\widehat{\beta_{\mathrm{NUREG\_1}}}$, $\widehat{\beta_{\mathrm{NUREG\_2}}}$, and new $\widehat{\beta_{\mathrm{PDS}}}$ with SINTEF example

	$\widehat{\beta_{\mathrm{NUREG\_1}}}$	$\widehat{\beta_{\mathrm{NUREG\_2}}}$	New $\widehat{\beta_{\mathrm{PDS}}}$
Equation	$\frac{N_{DU,CCF}}{N_{DU}}$	$\frac{2 \cdot N_{CCF}}{N_{DU,I} + 2 \cdot N_{CCF}}$	$\frac{\sum_{j=1}^{K} Y_j \left(Y_j - 1\right)}{(n-1) \sum_{j=1}^{K} Y_j}$
Shutdown valves	0.2181	0.0877	0.0657
Blowdown valves	0.2329	0.1250	0.0370
PSVs	0.2162	0.1594	0.0180
Level transmitter	0.2407	0.1277	0.0335

Chapter 6

Summary and Recommendations for Further Work

6.1 Summary

In this thesis, definitions and classifications of the CCF are investigated from various industries. From the investigation, four core aspects of the definition for the CCF are extracted, and improved classifications for root causes and coupling factors of the CCF are suggested.

Based on these basic knowledge, the CCF analysis procedure is investigated with literatures from the nuclear industry. Through the review of NUREG reports, a flow diagram which explains how NUREG report has developed is proposed. In addition, the relationship among definition of the CCF, causes of the CCF, CCF parametric model, parameter estimation and system model is provided with relevant illustration.

To find out that how CCFs are applied to the risk assessment, incorporation of CCFs in the fault tree analysis is investigated. In this process, it is realized that the CCF parametric model carries an important meaning in CCF analysis.

CCF parametric model which is used to quantify implicit causes of CCF is introduced. Based on the limitation of the CCF parametric models, the background of the PDS method is explained and its limitations are also presented.

In this thesis, how to derive the NUREG estimators ($\beta_{\widehat{NUREG\_1}}$ and $\beta_{\widehat{NUREG\_2}}$) and the PDS estimator ($\widehat{\beta_{PDS}}$) are investigated, therethrough the relationship between these three estimators and the standard beta-factor model can be figured out. The NUREG estimators ($\beta_{\widehat{NUREG\_1}}$ and $\beta_{\widehat{NUREG\_2}}$) and the PDS estimator ($\widehat{\beta_{PDS}}$) are related to the standard beta-factor model. $\beta_{\widehat{NUREG\_1}}$

is more directly connected to the standard beta-factor model, $\widehat{\beta_{NUREG\_2}}$ is motivated by the Multiple Greek Letter model, and $\widehat{\beta_{PDS}}$ is inspired by the modified beta-factor model (Fig.24).

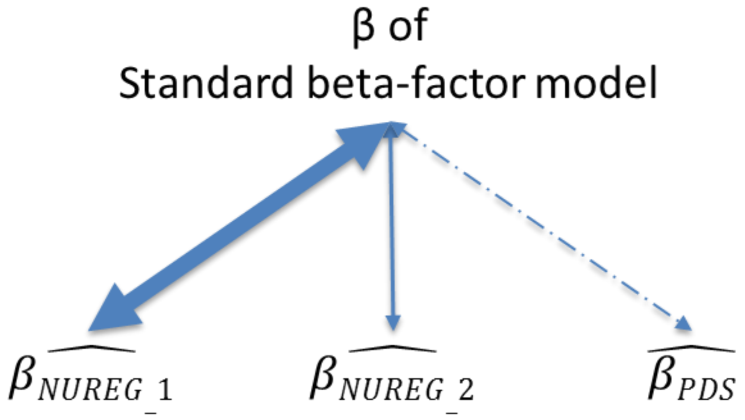

Figure 24: Connection between the β in the standard beta-factor model, $\widehat{\beta_{NUREG\_1}}$, $\widehat{\beta_{NUREG\_2}}$, and $\widehat{\beta_{PDS}}$

In the PDS method, the PDS estimator is evaluated to reflect operational data into the β value. Several assumptions are needed to derive the PDS estimator, and one of the assumptions is discussed in this thesis; "The size of CCF group equals the CCF event with most failures"

To investigate how appropriate this assumption, Q_{koon} (the probability that the *koon* system is in a failed state) is calculated by using the Multiple Beata Factor model. As a result of this calculation, we may conclude that the assumption should be reconsidered.

To overcome the limitation of the PDS estimator which is caused by the assumption, improved approach for determining the PDS estimator is proposed. The main idea is that most common event (individual failure) can be used to estimate the CCF group size, and the Individual Failure Ratio (IFR) is introduced. The IFR is defined as the ratio of single component failure to the total number of component failure.

In the proposed approach, it is assumed that the IFR equal to the ratio of the probability of one component in a failed state to the probability of all components are in a failed state. Then, the CCF group size is adjusted to satisfy this assumption.

A case study is conducted to apply suggested IFR approach, and SINTEF data is selected as input data. New CCF group size is estimated with proposed approach for ESD/PSD valves, blowdown valves, fire dampers, PSVs, point gas detectors, flame detectors, smoke detectors, level transmitters, pressure transmitters and flow transmitters. In addition, it is assessed that how $\widehat{\beta_{PDS}}$ is affected by the different CCF group size (old and new CCF group size). The $\widehat{\beta_{PDS}}$ with PDS method assumption (used old CCF group size) is larger than the $\widehat{\beta_{PDS}}$ with newly suggested assumption (used new CCF group size). We may conclude that $\widehat{\beta_{PDS}}$ could be overestimated with the assumption that *"maximum number of failure components equals to the CCF group size"*.

6.2 Discussion

This thesis is expected to provide two kinds of contributions. The first contribution is to help readers understand basic concepts of CCFs. Through sub-objective (1), (2) and (3) established in Section 1.2, this thesis introduced CCF from its definition to the recently developed CCF analysis method; the PDS method.

The other contribution is to suggest improved approach to determine the PDS estimator. More specifically, this thesis develops IFR approach to estimate more realistic CCF group size, and demonstrates the new approach with a case study.

With these two contributions, this thesis is ultimately expected to contribute to reduce the occurrence of CCFs in safety critical systems of oil and gas industries.

As discussed in section 5.2, IFR approach still has some challenges. One challenge is that in some cases, the $\widehat{\beta_{PDS}}$ value is extremely low or cannot be obtained with the IFR approach. Some trends of this problem are identified, but more number of case studies are required to verify the IFR approach and the trend of extremely low beta values as stated in section 6.3. For more detailed discussion for the case study, the reader can refer to section 5.2.

6.3 Recommendations for future work

This thesis investigates one of challenging assumptions of PDS method, and suggests an improved approach to estimate the CCF group size. This study also conducts case studies with failure data of ten equipment, and estimates CCF group sizes using the improved approach. While couple of trends can be identified from the results of the case studies, one may argue that these trends are derived from limited number of case studies. With more number of case studies, we may verify the trends or we can derive additional trends that are not identified in this thesis. Increasing the number of case studies is the first further work.

Another further work is to explore another challenging assumption of PDS method. As mentioned in Section 4.1, there are two challenging assumptions in the PDS method, and this thesis investigated only one of the two assumptions. The unexplored assumption is "All n_j (CCF group size) have same value". The validity of this assumption also need to be discussed, and an improved approach should be developed, if necessary.

The last future work is about the check-list in PDS method, a generic beta factor is obtained from failure data, and a plant specific beta factor is estimated by a combination of the generic beta factor and a check-list. As stated in Section 3.3, the modification factors from the check-list are uniformly assumed for every type of equipment, while the value may significantly vary between equipment. This assumption should be explored and an improved approach should be suggested, if necessary.

Appendix A Acronyms

CCF	common cause failure
CCFBE	common cause failure basic event
DU	dangerous undetected
ESD	emergency shutdown
IEC	international electrotechnical commission
IFR	individual failure ratio
MBF	multiple beta factor
MLE	maximum likelihood estimate
NUREG	US nuclear regulatory commission
PFD	probability of failure on demand
PSD	process shutdown
PSV	pressure safety valve

Appendix B CCF root cause classification

1. CCF root cause classification of NUREG/CR 6268 [28]

No.	Root Cause Category	Root Cause
1	Design/ Construction/ Manufacture	• Design error • Manufacturing error • Installation/ construction error • Design modification error
2	Operations/ Human Error	• Accidental action • Inadequate/ incorrect procedure • Failure to follow procedure • Inadequate training • Inadequate maintenance
3	External Environment	• Fire/ smoke • Humidity/ moisture • High/ low temperature • Electromagnetic field • Radiation • Bio-organisms • Contamination/ dust/ dirt • Acts of nature (wind/ flood/ lightning/ snow/ ice)
4	Internal to Component	• Normal wear • Internal environment • Early failure
5	State of Other Component	• Supporting system • Inter-connection
6	Unknown/ Other	

2. CCF root cause classification of Paula, et al. [16]

No.	Root Cause Category	Root Cause
1	Design	• Requirements/ specifications inadequacy • Error or inadequacy in design realization • Limitations (financial, spatial)
2	Manufacturing	• Error or inadequacy
3	Construction, installation, and commissioning	• Error or inadequacy
4	Maintenance	• Failure to follow procedures • Lack of procedures • Supervision inadequacy • Communication problems among maintenance teams • Maintenance training inadequacy
5	Operation	• Failure to follow procedures • Defective procedures • Supervision inadequacy • Communication problems among operating staff • Operator training inadequacy
6	Environmental	• Stresses (chemical reaction, moisture, pressure, etc.) • Energetic (fire, flood, seismic, etc.)

3. CCF root cause classification of NEA [18]

No.	Root Cause Category	Root Cause
1	State of other components	• The cause of the state of the component under consideration is due to the state of another component
2	Design, manufacture or construction inadequacy	• Actions and decisions taken during design, manufacture, or installation of components, both before and after the plant is operational
3	Abnormal environmental stress	• Causes related to a harsh environment that is not within component design specifications
4	Human actions	• Causes related to errors of omission or commission on the part of plant staff or contractor staff.
5	Maintenance	• All maintenance not captured by human actions or procedure inadequacy
6	Internal to component, piece part	• Malfunctioning of parts internal to the component (phenomena such as normal wear or other intrinsic failure mechanisms)
7	Procedure inadequacy	• Ambiguity, incompleteness, or error in procedures for operation and maintenance of equipment
8	Other, unknown	

4. CCF root cause classification of US DOE [33]

No.	Root Cause Category	Root Cause
1	Equipment/ Material Problem	• Defective or failed part • Defective or failed material • Defective weld, braze, or soldered joint • Error by manufacturer in shipping or marking • Electrical or instrument noise • Contamination
2	Procedure Problem	• Defective or inadequate procedure • Lack of procedure
3	Personnel Error	• Inadequate work environment • Inattention to detail • Violation of requirement or procedure • Verbal communication problem • Other human error
4	Design Problem	• Inadequate man-machine interface • Inadequate or defective design • Error in equipment or material selection • Drawing, specification, or data errors
5	Training Deficiency	• No training provided • Insufficient practice or hands-on experience • Inadequate content • Insufficient refresher training • Inadequate presentation or materials
6	Management Problem	• Inadequate administrative control • Work organizations/ planning deficiency • Inadequate supervision • Improper resource allocation • Policy not adequately defined, disseminated, or enforced • Other management problem
7	External Phenomenon	• Weather or ambient condition • Power failure or transient • External fire or explosion • Theft, tampering, sabotage, or vandalism

Appendix C CCF coupling factor classification

1. CCF coupling factor classification of NUREG/CR 6268 [28]

No.	Coupling Factor Category	Coupling Factor
1	Hardware Quality	• Manufacturing attributes • Installation/ construction attributes
2	Design Based	• Component internal parts • System configuration
3	Maintenance	• Maintenance/ test/ calibration schedule • Maintenance/ test/ calibration procedure • Maintenance/ test/ calibration staff
4	Operational	• Operating procedure • Operating staff
5	Environmental	• External environment • Internal environment

2. CCF coupling factor classification of NEA [18] and NUREG/CR-5485 [56]

No.	Coupling Factor Category	Coupling Factor
1	Hardware Based	• Hardware design - Same physical appearance - System layout/ configuration - Same component internal parts - Same maintenance/ test/ calibration characteristics • Hardware quality - Manufacturing attributes - Construction/ installation attributes
2	Operation Based	• Same operating staff • Same operating procedure • Same maintenance/ test/ calibration schedule • Same maintenance/ test/ calibration staff • Same maintenance/ test/ calibration procedures
3	Environment Based	• Same plant location • Same component location • Internal environment/ working medium

3. CCF coupling factor classification of Childs and Mosleh [19]

No.	Coupling Factor Category	Coupling Factor
1	Common operational usage	• Age • Maturity
2	Shared work environment	• Proximity - Redundant elements near each other - Elements to external equipment or systems • Same medium - Ambient air - Liquid (cooling, process chemical) - Solid (mounting area)
3	Functional coupling	• Same energy or utility source • Same input or output • Same load or load medium
4	Common personnel	• Design • Installation/ construction • Operations • Maintenance
5	Documentation	• Incomplete or incorrect procedures, displays, drawings, or training • Procedure steps fail to include adequate barriers for error
6	Others	• Common marking, labelling, display ambiguities • Similarity in components (manufacturer, material, technology)

4. CCF coupling factor classification of Ericson [57]

No.	Coupling Factor Category	Coupling Factor
1	Hardware-based	• Same physical appearance • System layout/ configuration • Same component internal parts • Same maintenance, test, and/or calibration characteristics • Manufacturing attributes • Construction and installation attributes
2	Operational- based	• Same operating staff • Same operating procedure • Same maintenance, test, and/or calibration schedule • Same maintenance, test, and/or calibration staff • Same maintenance, test, and/or calibration procedures
3	Environmental-based	• Same system location • Same component location • Internal environment/ working medium
4	Software-based	• Common algorithms • Common data • Common requirements

Appendix D Result of the case study

Blowdown valves

In total, 73 failures were defined as DU failures for blowdown valves from the six operational reviews. The total population of blowdown valves included 228 valves. Detailed explanation of the CCF events are in section 4.3 of [26].

Table D. 1: Number of failed components of blowdown valves

	Number of failed components
DU failures	73
CCF events	4
CCF1	2
CCF2	3
CCF3	10
CCF4	2

Table D. 2: $\widehat{\beta_{PDS}}$ for the two CCF group sizes (10 and 38)

	CCF group size	PDS estimator ($\widehat{\beta_{PDS}}$)
Old	10	0.1522
New	38	0.0370

The ratio of single components failure to the total number of component failure is 56/73 ≈ 0.7671.

As we can see in Table D. 1, most failures of the CCF event is 10, and the ratio of single component failure is 53.7% when the CCF group size is assumed to the most failures. The CCF group size is adjusted to make the single failure ratio from 53.7% to 76.7%. The single component failure ratio become 76.7% when the CCF group size is 38 (Fig. D. 1).

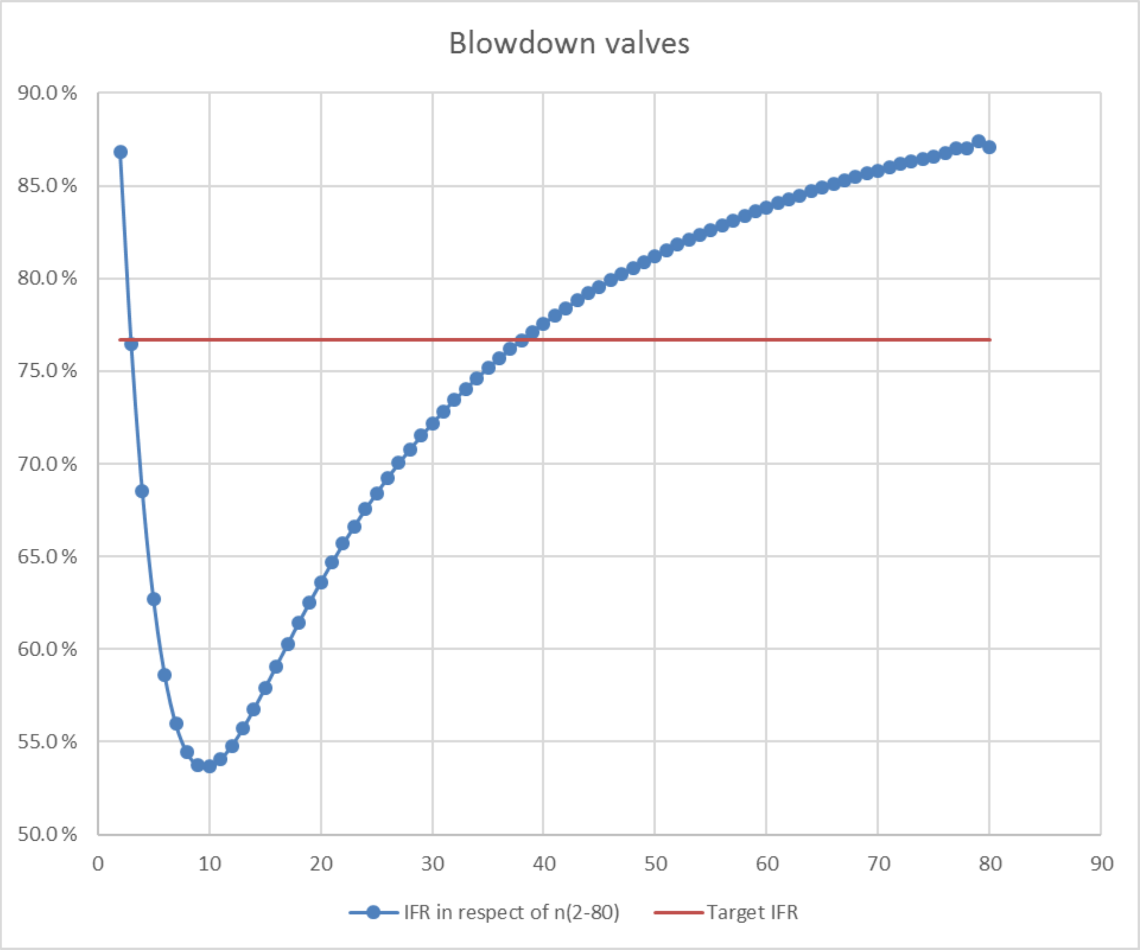

Figure D. 1: For blowdown valves, the single failure ratio according to the CCF group size in the rage from 2 to 80

Fire dampers

In total, 44 failures were defined as DU failures for fire dampers from the six operational reviews. 458 fire dampers made up the aggregated population from the six facilities. Detailed explanation of the CCF events are in section 4.3 of [26]

Table D. 3: Number of failed components of fire dampers

	Number of failed components
DU failures	44
CCF events	6
CCF1	6
CCF2	6
CCF3	4
CCF4	3
CCF5	2
CCF6	2

Table D. 4: $\widehat{\beta_{PDS}}$ for the CCF group size

	CCF group size	PDS estimator ($\widehat{\beta_{PDS}}$)
Old	6	0.3727
New	N/A	N/A

The ratio of single components failure to the total number of component failure is 21/44 ≈ 0.4773. Because of relatively small number of DU failures, the CCF group size cannot be obtained.

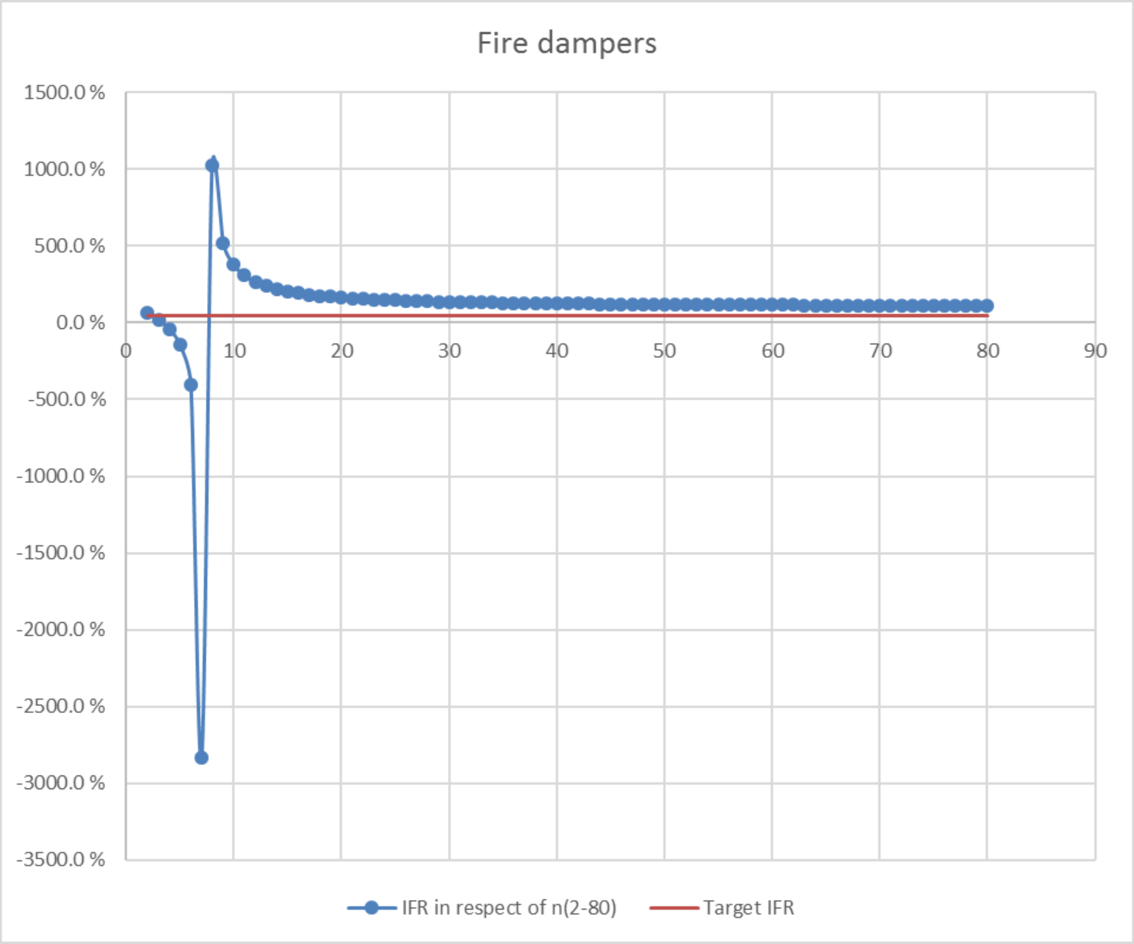

Figure D. 2: For fire dampers, the single failure ratio according to the CCF group size in the rage from 2 to 80

PSVs

In total, 148 failures were defined as DU failures for the facilities where PSV valves have been reviewed constituting a total of 2356 PSVs. Detailed explanation of the CCF events are in section 4.3 of [26]

Table D. 5: Number of failed components of pressure safety valves

	Number of failed components
DU failures	148
CCF events	11
CCF1	6
CCF2	3
CCF3	2
CCF4	2
CCF5	2
CCF6	2
CCF7	2
CCF8	5
CCF9	3
CCF10	3
CCF11	2

Table D. 6: $\widehat{\beta_{PDS}}$ for the two CCF group sizes (6 and 31)

	CCF group size	PDS estimator ($\widehat{\beta_{PDS}}$)
Old	6	0.1081
New	31	0.0180

The ratio of single components failure to the total number of component failure is 116/148 ≈ 0.7838.

As we can see in Table D. 5, most failures of the CCF event is 6, and the ratio of single component failure is 63.3% when the CCF group size is assumed to the most failures. The CCF group size is adjusted to make the single failure ratio from 63.3% to 78.4%. The single component failure ratio become 78.3% when the CCF group size is 31 (Fig. D. 3).

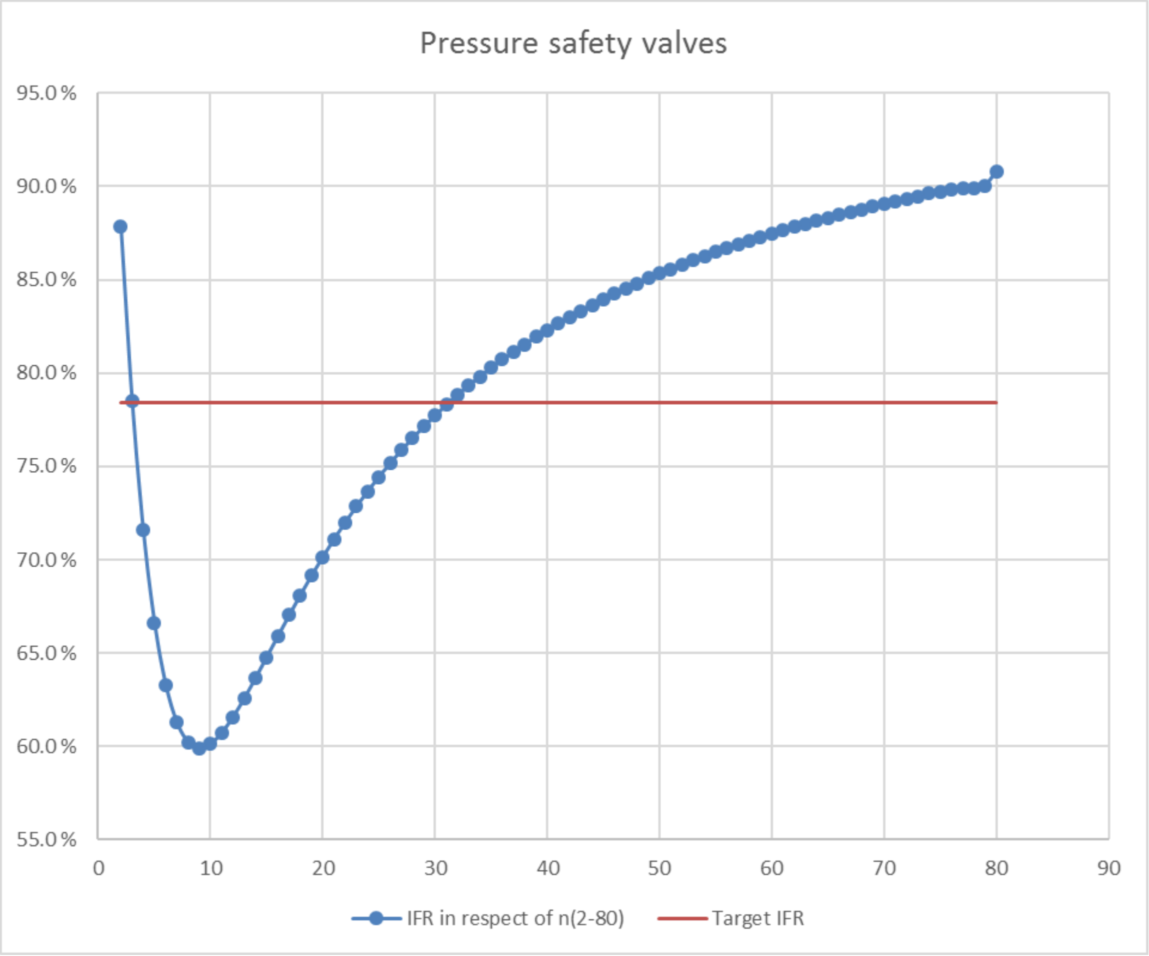

Figure D. 3: For pressure safety valves, the single failure ratio according to the CCF group size in the rage from 2 to 80

Gas detectors (For point)

In total, 59 failures were defined as DU failures for point gas detectors from the six operational reviews. This included a total population of 1341 point gas detectors. Detailed explanation of the CCF events are in section 4.3 of [26]

Table D. 7: Number of failed components of gas detectors for point

	Number of failed components
DU failures	59
CCF events	4
CCF1	10
CCF2	4
CCF3	2
CCF4	10

Table D. 8: $\widehat{\beta_{PDS}}$ for the CCF group size

	CCF group size	PDS estimator ($\widehat{\beta_{PDS}}$)
Old	10	0.3653
New	N/A	N/A

.Because of relatively small number of DU failures, the CCF group size cannot be obtained.

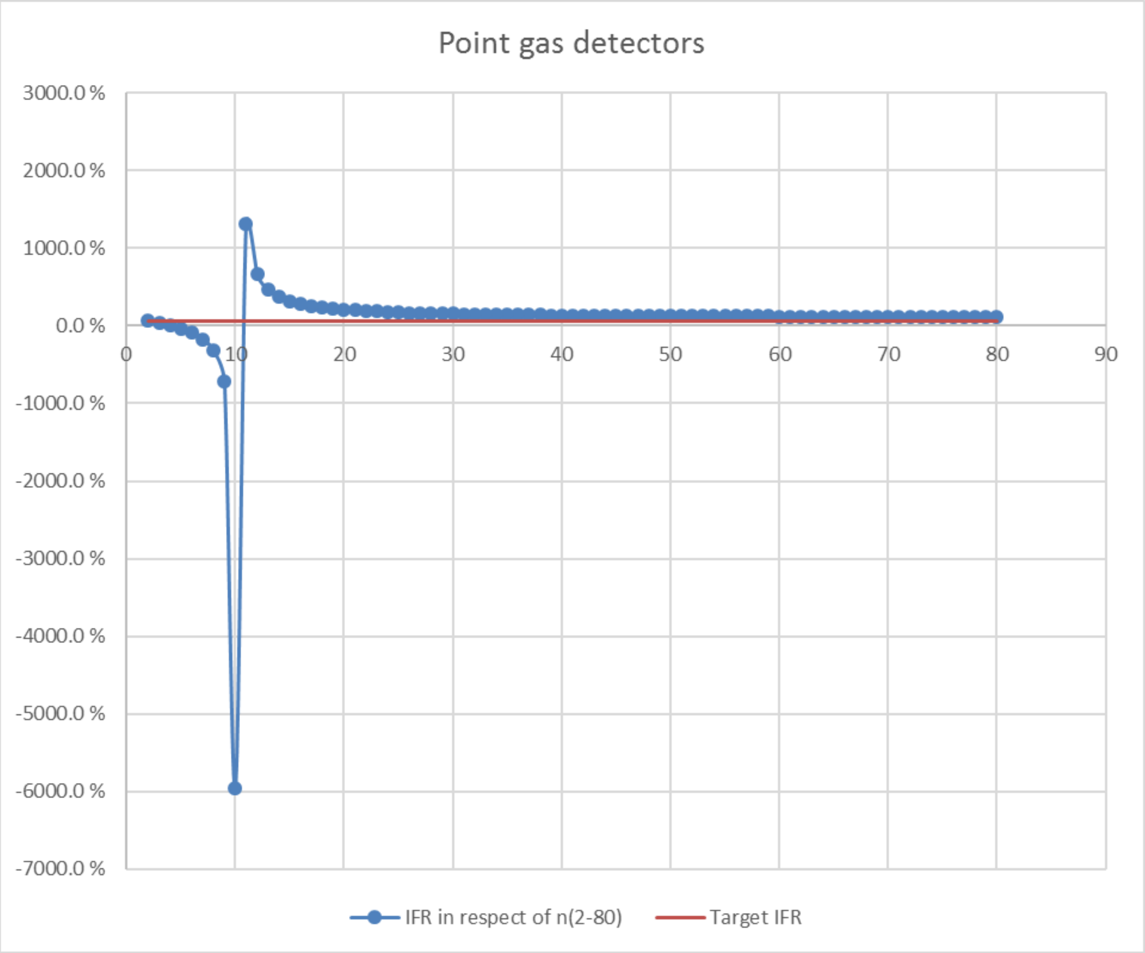

Figure D. 4: For point gas detectors, the single failure ratio according to the CCF group size in the rage from 2 to 80

Flame detectors

In total, 23 failures were defined as DU failures for flame detectors from the six operational reviews. This included a total of 1780 detectors. Detailed explanation of the CCF events are in section 4.3 of [26].

Table D. 9: Number of failed components of flame detectors

	Number of failed components
DU failures	23
CCF events	3
CCF1	4
CCF2	2
CCF3	2

Table D. 10: $\widehat{\beta_{PDS}}$ for the two CCF group sizes (4 and 7)

	CCF group size	PDS estimator ($\widehat{\beta_{PDS}}$)
Old	4	0.2319
New	N/A	N/A

The ratio of single components failure to the total number of component failure is 15/23 ≈ 0.6522. However, relatively small number of DU failures, the CCF group size cannot be obtained.

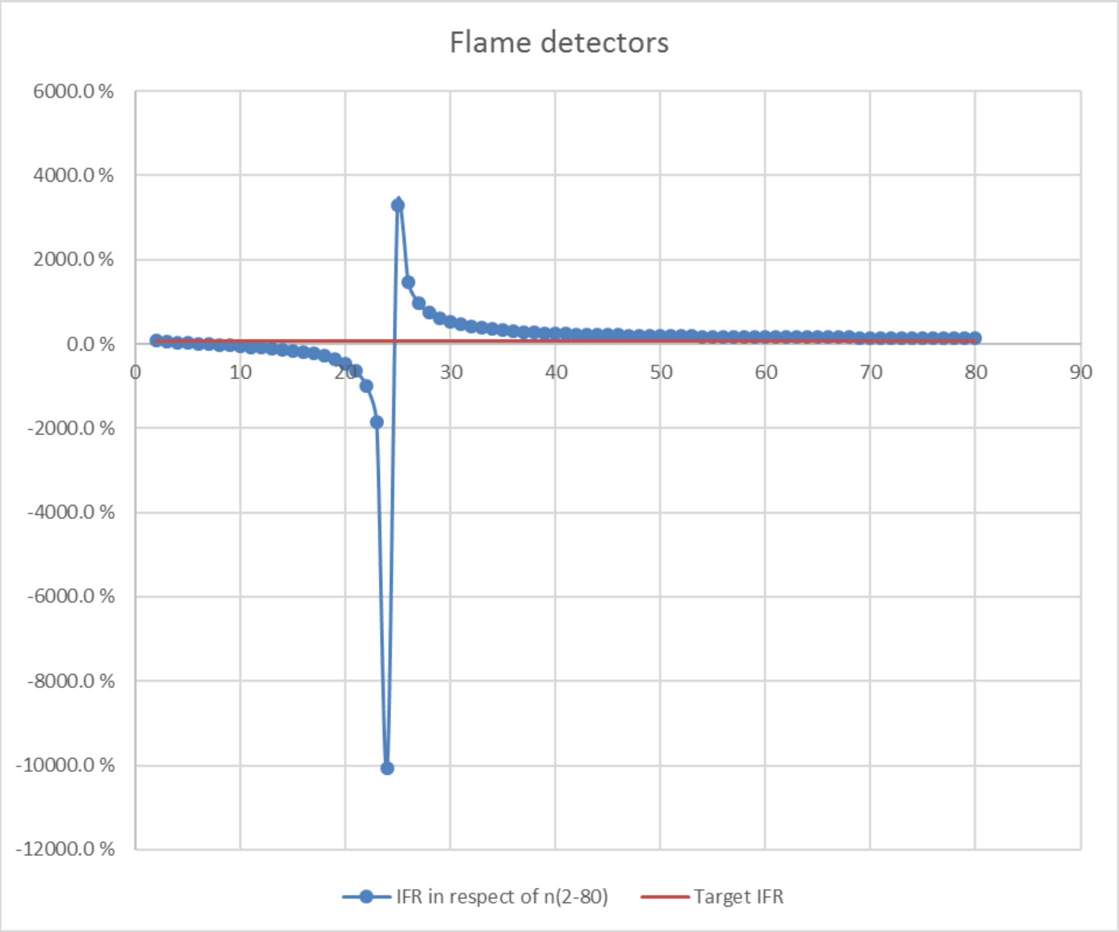

Figure D. 5: For flame detectors, the single failure ratio according to the CCF group size in the rage from 2 to 80

Smoke detectors

Based on a total population of some 3945 flame detectors, 41 failures were defined as DU failures for smoke detectors from the six operational reviews. It should be noted that 25 of these were revealed on the same installation. These detectors had limited diagnostics and did not give any alarm when they had failed. Detailed explanation of the CCF events are in section 4.3 of [26].

Table D. 11: Number of failed components of smoke detectors

	Number of failed components
DU failures	41
CCF events	5
CCF1	2
CCF2	2
CCF3	2
CCF4	2
CCF5	3

Table D. 12: $\widehat{\beta_{PDS}}$ for the two CCF group sizes (3 and 76)

	CCF group size	PDS estimator ($\widehat{\beta_{PDS}}$)
Old	3	0.1707
New	76	0.0046

The ratio of single components failure to the total number of component failure is 30/41 ≈ 0.7317.

As we can see in Table D. 11, most failures of the CCF event is 3, and the ratio of single component failure is 71.7% when the CCF group size is assumed to the most failures. The CCF group size is adjusted to make the single failure ratio from 71.7% to 73.2%. The single component failure ratio become 73.2% when the CCF group size is 76 (Fig. D. 6).

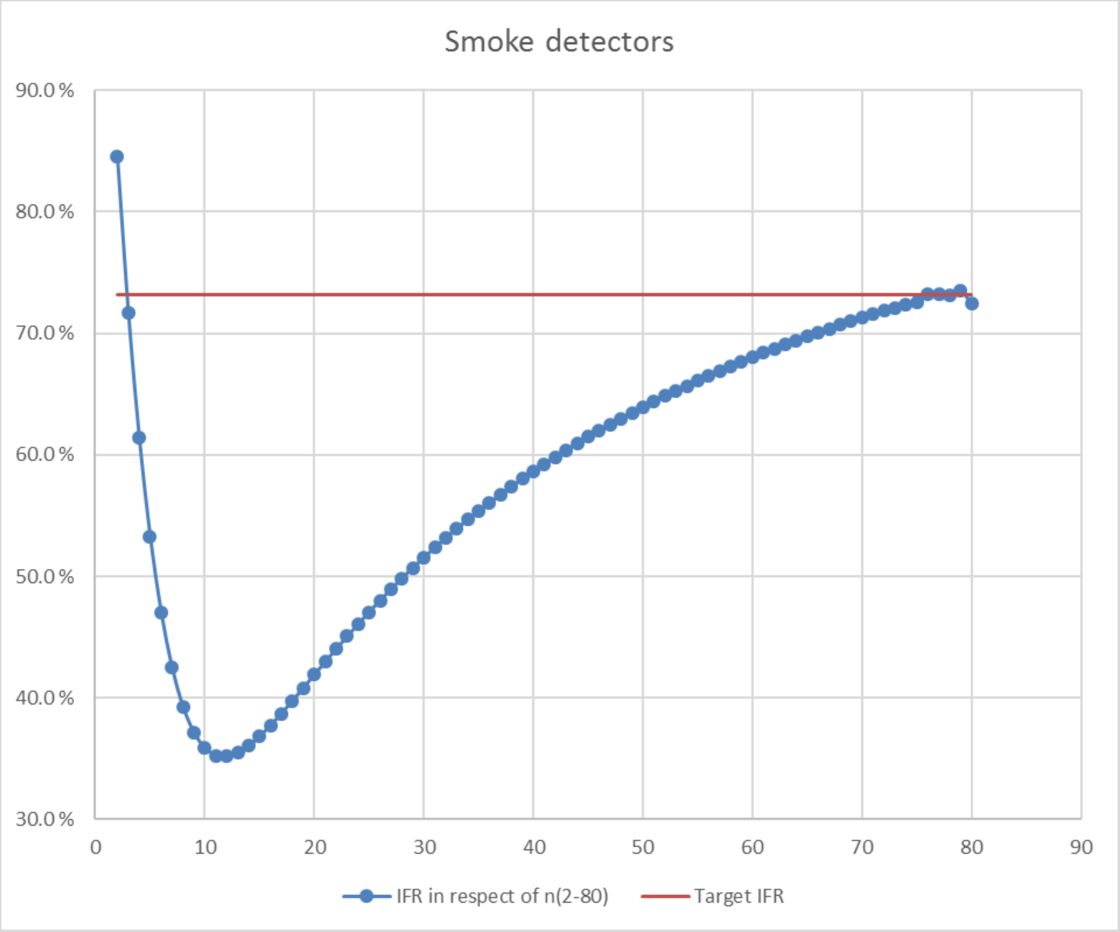

Figure D. 6: For smoke detectors, the single failure ratio according to the CCF group size in the rage from 2 to 80

For smoke detector, the obtained new CCF group size is relatively large, and the new $\widehat{\beta_{PDS}}$ is much smaller than the others. Further study need to be conducted to investigate the reason of these values.

Level transmitters

In total, 54 failures were defined as DU failures for level transmitters from the six operational reviews. The total population included 346 level transmitters. Detailed explanation of the CCF events are in section 4.3 of [26].

Table D. 13: Number of failed components of level transmitters

	Number of failed components
DU failures	54
CCF events	3
CCF1	9
CCF2	2
CCF3	2

Table D. 14: $\widehat{\beta_{PDS}}$ for the two CCF group sizes (9 and 43)

	CCF group size	PDS estimator ($\widehat{\beta_{PDS}}$)
Old	9	0.1759
New	43	0.0335

The ratio of single components failure to the total number of component failure is 41/54 ≈ 0.7593.

As we can see in Table D. 13, most failures of the CCF event is 9, and the ratio of single component failure is 50.5% when the CCF group size is assumed to the most failures. The CCF group size is adjusted to make the single failure ratio from 50.5% to 75.9%. The single component failure ratio become 76.1% when the CCF group size is 43 (Fig. D. 7).

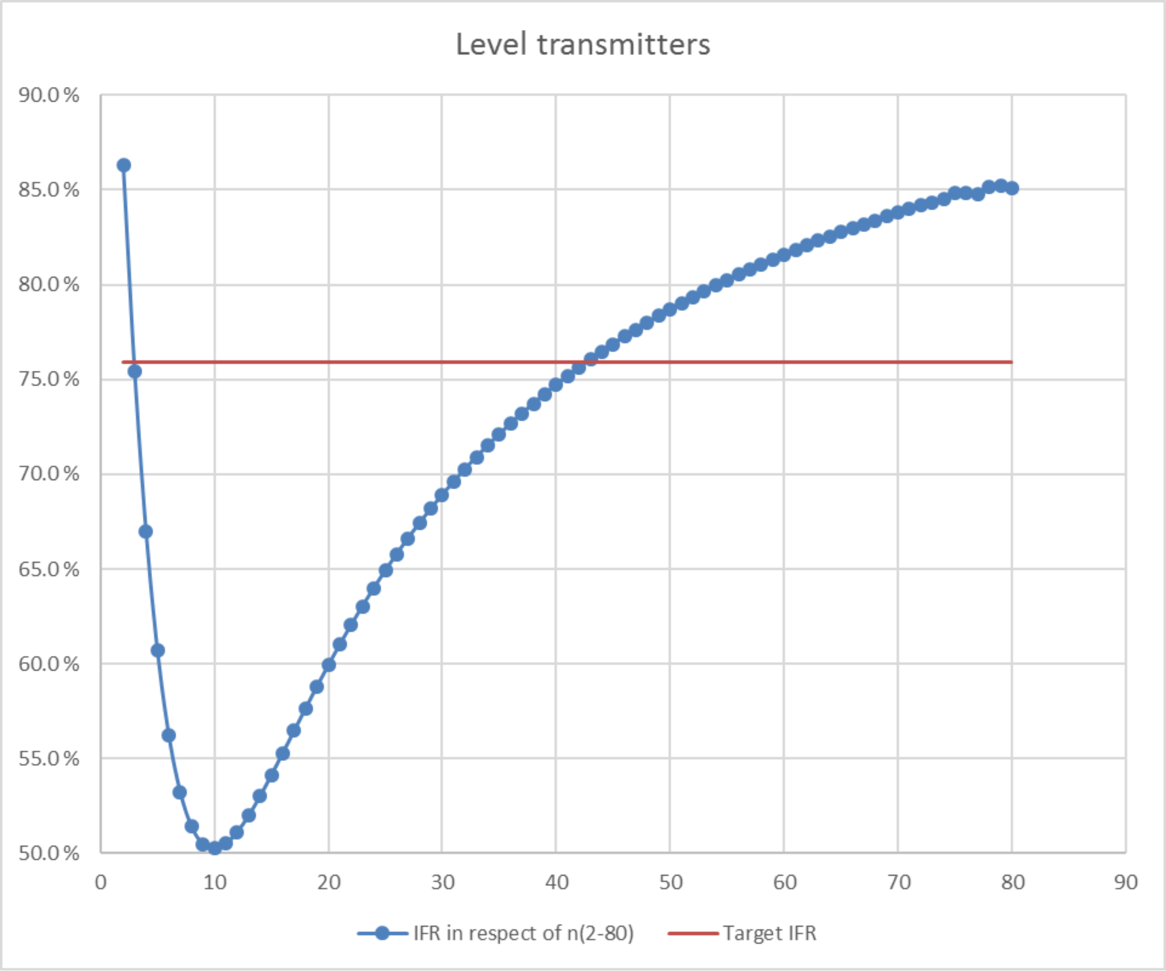

Figure D. 7: For level transmitters, the single failure ratio according to the CCF group size in the rage from 2 to 80

Pressure transmitters

In total, 44 failures were defined as DU failures for pressure transmitters from the six operational reviews. This was based on a total population of 917 pressure transmitters. Detailed explanation of the CCF events are in section 4.3 of [26].

Table D. 15: Number of failed components of pressure transmitters

	Number of failed components
DU failures	44
CCF events	4
CCF1	5
CCF2	3
CCF3	2
CCF4	3

Table D. 16: $\widehat{\beta_{PDS}}$ for the CCF group size

	CCF group size	PDS estimator ($\widehat{\beta_{PDS}}$)
Old	5	0.1932
New	N/A	N/A

The ratio of single components failure to the total number of component failure is 31/44 ≈ 0.7045. Because of relatively small number of DU failures, the CCF group size cannot be obtained.

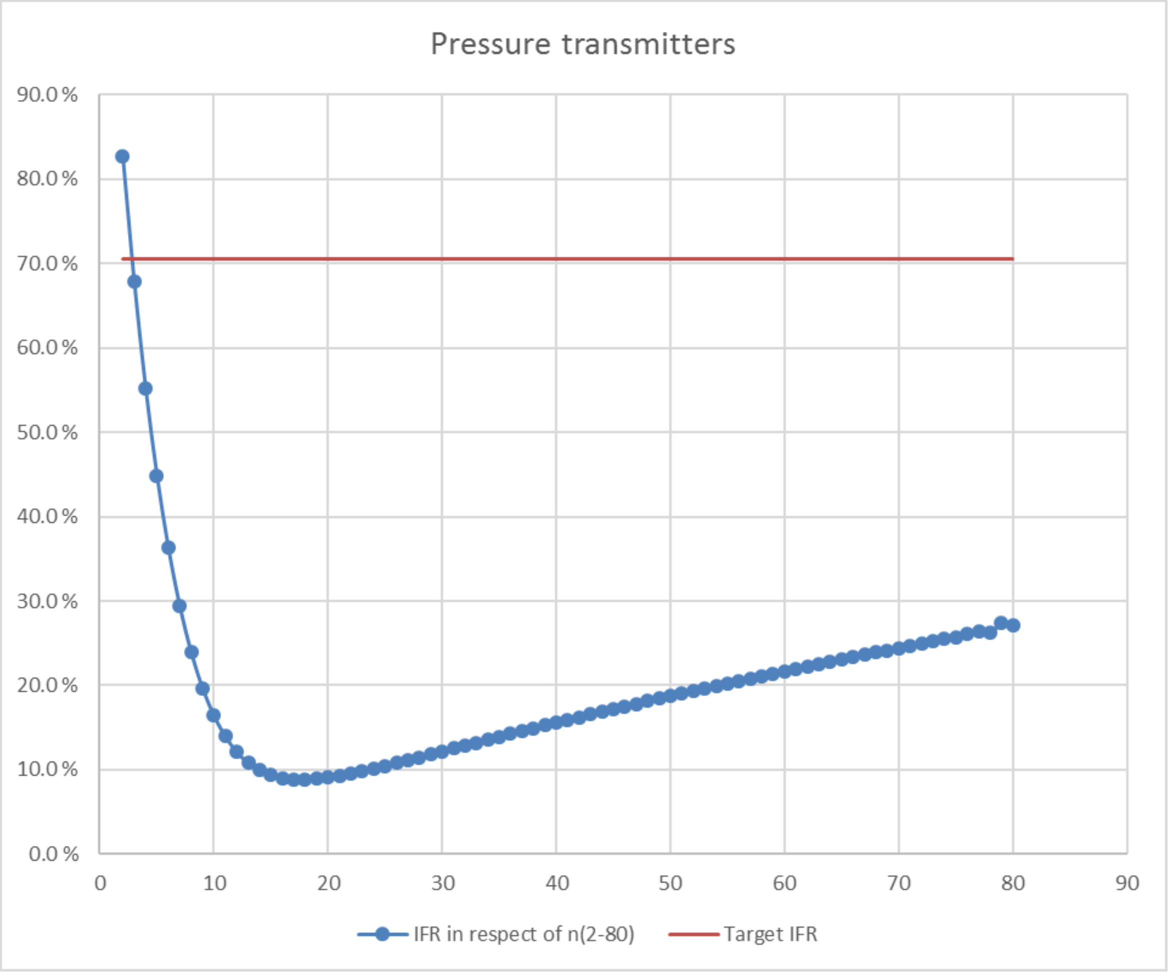

Figure D. 8: For pressure transmitters, the single failure ratio according to the CCF group size in the rage from 2 to 80

Flow transmitters

11 DU failures have been revealed for flow transmitters based on a total population of 114 transmitters. 2 CCF events were registered. Detailed explanation of the CCF events are in section 4.3 of [26].

Table D. 17: Number of failed components of flow transmitters

	Number of failed components
DU failures	11
CCF events	2
CCF1	4
CCF2	2

Table D. 18: $\widehat{\beta_{PDS}}$ for the CCF group size

	CCF group size	PDS estimator ($\widehat{\beta_{PDS}}$)
Old	4	0.4242
New	N/A	N/A

Because of relatively small number of DU failures, the CCF group size cannot be obtained.

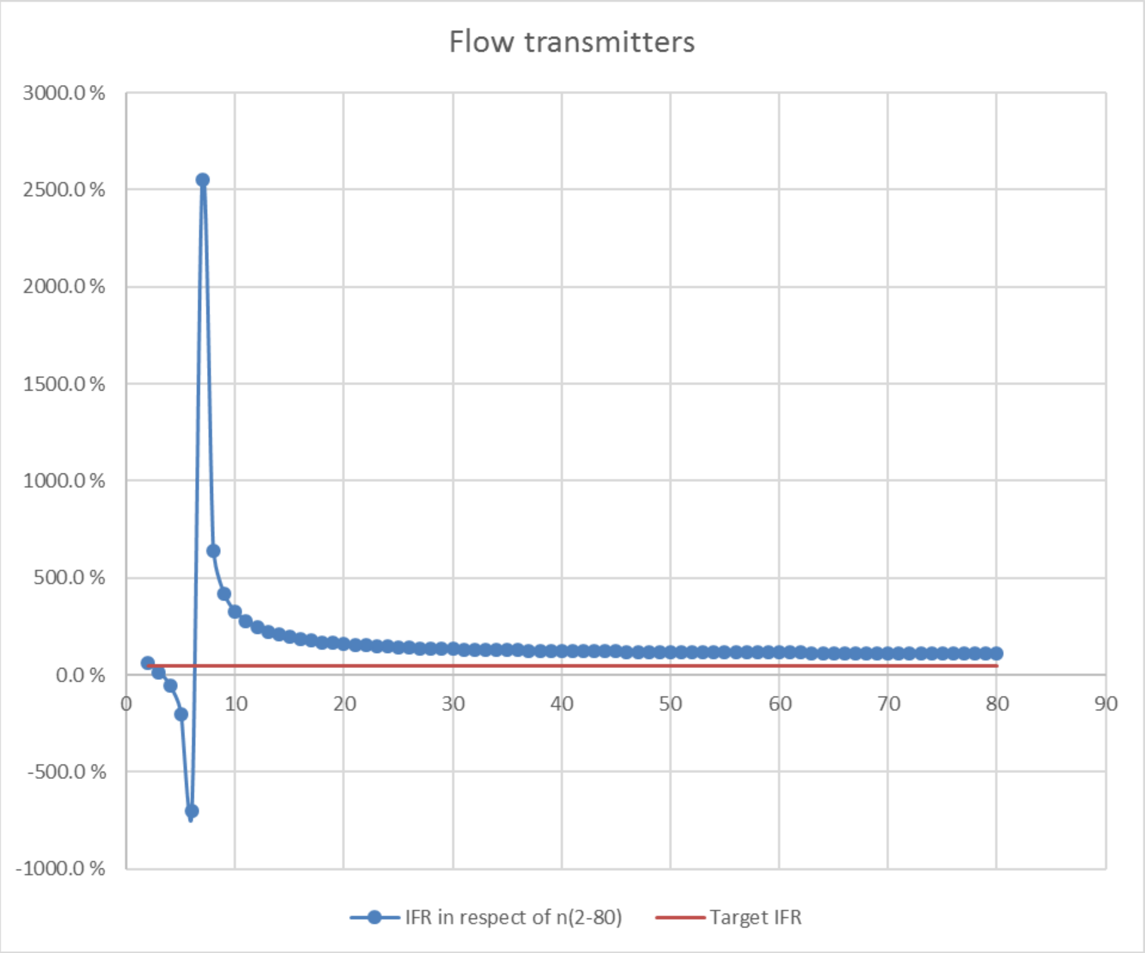

Figure D. 9: For flow transmitters, the single failure ratio according to the CCF group size in the rage from 2 to 80

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