C-BOOK: COMMON CAUSE FAILURE RELIABILITY DATA BOOK

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The amount of available common cause failure (CCF) data from the ICDE project allows estimating and presenting CCF reliability data. In 2009, a three-year Nordic/German programme was initiated to continue the work using the results of the ICDE activities and the method development for CCF parameter estimation. Component specific reports with qualitative and quantitative CCF data have been developed and published by the Nordic PSA Group (NPSAG). As a final step in the quantitative work, the objective is to create a CCF data book based on the component reports. The overall objective was divided into:

- *Quantify the data in a transparent way*
- *Present a data book with generic and plant specific results*
- *Apply the common procedure and model for quantification of CCF events in an Excel tool*

The C-book shall provide the Nordic PSA practitioners with CCF reliability data for the dependency analysis that is considered in the compulsory, probabilistic safety assessments (PSA) of nuclear power plants. The C-Book should be considered as an important step in the continuous effort to collect and analyse data on CCF of safety components at NPPs, and to improve quality of data in PSA.

A procedure including all steps from CCF event input data, via event impact vectors, to final CCF parameters has been developed and validated within a Nordic/German working group on common cause failure analysis. The procedure provides a common basis for methods and guidelines for data classification and assessment, and by establishing a format to allow data to be shared for quantifications and to provide interpretation of raw data for exchange and use in quantification models.

Component specific reports with qualitative and quantitative CCF data have been developed and published by the Nordic PSA Group (NPSAG) for centrifugal pumps, emergency diesel generators, motor operated valves, check valves, circuit breakers, level measurements and batteries. The input data to the analyses represents homogenous subsets of data reported to the ICDE, where events are analysed and reviewed in a team review to achieve quality assurance. The quantification tasks are presented in a transparent way in an Excel tool, which includes the data analysis for impact vector construction and Bayesian parameter estimation.

The C-book presents tables with generic and plant specific CCF reliability data. The tables include CCF rates, probabilities and alpha factors for a given test interval. Generic data is published by the NPSAG. The plant specific data and the enclosed Excel tool is only available for the NPSAG members. The quantitative results have been validated in a quantitative application with RiskSpectrums CCF models, specifically the Alpha-4 Factor model and the Alpha-4 Staggered model. A RiskSpectrum parameter key identifier has been developed for simplified import of data.

A comprehensive procedure has led to the development of a CCF data book, which contains generic and plant specific CCF rates, probabilities and alpha factors. The C-book will improve the quality of data for the dependency analysis in the PSA for nuclear power plants.

I. INTRODUCTION

Common Cause Failure (CCF) events can significantly impact the availability of safety systems of nuclear power plants. In recognition of this, CCF data are systematically being collected and analysed in several countries under the framework of the ICDE (International Common cause failure Data Exchange) project, Ref. 1. The data collection and qualitative analysis results in qualitative CCF information that can be used for the assessment of the effectiveness of defences against CCF events and of the importance of CCF events in the PSA framework.

A comprehensive procedure including all steps from CCF event input data as provided in ICDE, via event impact vectors, to final CCF parameters has been developed and validated within a Nordic/German working group on common cause failure analysis. The performed work and obtained results has been presented in Ref. 2.

In 2009 a three year Nordic/German programme was initiated called NAFCS, (Nordic work group for CCF studies) to continue the work using the results of the ICDE activities and the method development for CCF parameter estimation. The overall objective was to develop and present qualitative and quantitative results concerning CCF events from the Nordic and German plants. Within this programme, component specific reports with qualitative and quantitative CCF data have been developed. The purpose of the component reports is to capture performed work within the area and to carry out complementary and specific qualitative and quantitative analysis for the component in question. The reports have been published by the Nordic PSA Group (NPSAG), Ref. 3-9.

I.A. Challenges when quantifying CCF

To achieve quality assurance of the data input to the analyses in a transparent way, several challenges exists and have to be considered. For the quantitative analysis, component groups and events need to be assessed, divided and grouped to assure that the quantification is made on a homogenous and applicable set of data. The main challenges to consider are summarized in TABLE I below.

TABLE I. Challenges when quantifying CCF.

Challenge	Description
Event set	Answer whether the completeness of CCF event set covers the available national CCF experience.
Observation time	Answer whether the completeness of group observation data correctly estimates the group years in relation to the reported event data set.
Applicability of data	Decide via individual specific assessment whether to take events and groups into account or not in the CCF reliability data to assure a homogenous set of data.
Event interpretation with respect to CCF combinations	Independent of the used quantification model, probabilities for different CCF combinations have to be calculated through transformation of component impairment vector to event impact vector.
Parameter estimation and transformation of rates	Determine method for estimating failure rates (frequencies), when failure or degradation event data is available from one or more units (components, systems or plants). For further treatment (to obtain other parameter such as probabilities, alpha factors, etc.) consideration of test policy, test interval, success criterion for the target plant and system must be made.

I.B. Objective and scope

The overall objective is to create a CCF data book similar to the Nordic T-book (reliability data book for single failures). The amount of available CCF data (from the ICDE project) allows estimating and presenting k out of n specific CCF rates as presented in the component reports. The resulting CCF failure rates and their percentiles forms the output data of the CCF data book.

The C-book provides with CCF reliability data for the dependency analysis that is considered in the compulsory, probabilistic safety assessments (PSA) of nuclear power plants. The C-Book should be considered as an important step in the continuous effort to collect and analyse data on CCF of safety components at NPPs, and to improve quality of data in PSA. The C-book includes CCF reliability data for the following components:

- Centrifugal Pumps
- Emergency Diesel Generators
- Check Valves
- Motor Operated Valves
- Level measurements
- Breakers
- Batteries

The component reports were published by the NPSAG during 2010-2014. Additional data have not been taken into account after the reports were published. The C-book presents essentially CCF rates. To complement the data, reliability data for CCF probabilities and alpha factors are provided through a basis for transformation of rates into probabilities or alpha factors. The use of alpha factors is dependent on the single failure rate and the CCF rates for k out of n failures. Hence, the generic alpha factor tables is limited to a specific single failure rate.

II. QUANTIFICATION METHODOLOGY

II.A. Introduction

The methodology for quantification is the procedure described in SSM report 2009:07, Ref. 2. The overall procedure is illustrated in Fig. 1.

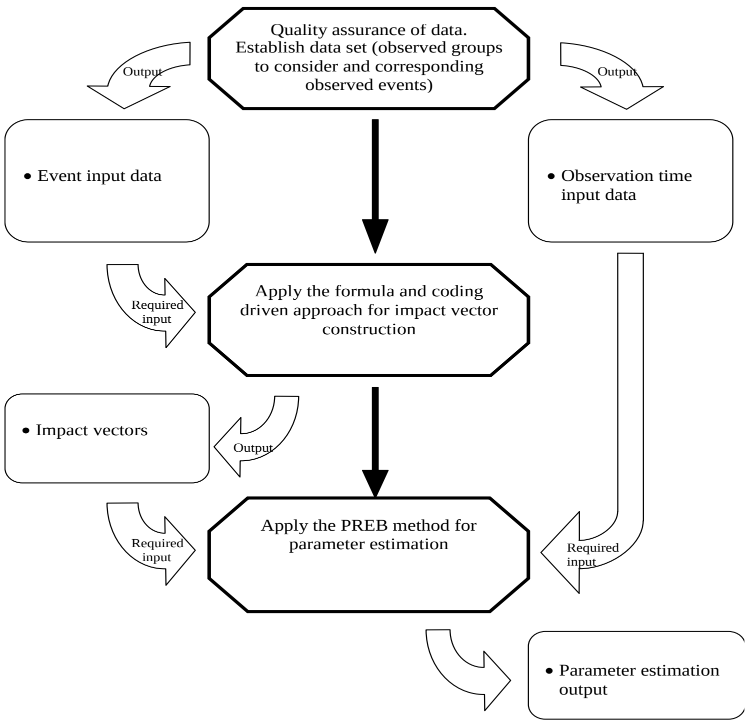

Fig. 1. Overall procedure of the methodology for quantification.

A comprehensive procedure including all steps from CCF event input data, via event impact vectors, to final CCF parameters has been developed and validated. The main objective was to establish a common procedure and model of quantification of CCF events. This was done by:

- Providing a common basis for methods and guidelines for data classification and assessment.
- Establishing format to allow data to be shared for quantifications and to provide interpretation of raw data for exchange and use in quantification models.

In the following sections are the steps described briefly and for further details see Ref. 2.

II.B. Quality assurance of data

The quality assurance of the input to any data analysis is of great importance. The following gives guidance on issues for review. The data needs to be evaluated concerning internal symmetry and homogeneity. In general, CCF events of a Common Cause Component Group (CCCG) belonging to a certain component type are supposed to be fully applicable to other component groups of this component type, i.e. internal symmetry. The data needs to be screened concerning homogeneity and once it is defined what groups at different plants that are to be included in the assessment (or rather how the data should be split up), the evaluation of events to be included can be performed. It cannot be stressed too strongly, that the quality of input data is a critical issue for any automatic treatment of this input data. It must be assured, that the input data is of high quality.

The quality procedures of CCF data generation follows a QA review form for each event to ensure this. The review process within the NAFCS project follows this form. The input data to the analyses represents homogenous subsets of data reported to the ICDE.

II.C. Impact vector construction method

The formula and coding driven (FCD) impact vector construction method has been developed using various approaches to select a suitable approach taking into account existing cases for diesels and pumps. For the agreed approach, there have been two basic requirements, i.e. it shall be defendable and it shall result in realistic modelling. The formula and coding driven approach is a systematic approach to interpret the component impairment vector into an event impact vector, see Fig. 2. The approach can be applied for quantitative analysis of CCF events and it fulfils the above basic requirements. It can be properly described with the following arguments:

- It takes the most conservative approach possible given the data, when stronger impairment is seen.
- It takes a less conservative approach when weak impairment as dominant observation is seen, because this is, what experts have been observed to do.
- On an average, the approach is still conservative in comparison with expert assessments.

- Event impact vector: expresses the conditional (on symptoms) failure probability, given an observed CCF, that different numbers of components would fail if an actual demand should occur during the presence of the CCF impact.
- Impairment vector: expresses the degradation of the individual components in a CCF group. The degradation scale ranges from; complete – degraded – incipient – working.

Fig. 2. Event impact vector vs. component impairment vector

The model is summarized in TABLE II. The High Bound approach is adopted for cases with indication of stronger impairment or no clear pattern. Otherwise, the less conservative approach is used to represent scenario based expert judgments for cases with indication of weak impairment as dominant observation.

TABLE II. Applied approach for impact vector construction.

	More than one C	At most one C
More than one D, I	High Bound applied	Scenario based approach
At most one D, I	High Bound applied	High Bound applied

II.C.1. *Construction of impact vectors*

The general flow in the impact vector construction is presented in Fig. 3. Steps 1-4 are concerned with the basic evaluation of CCF parameters for a defined component group, failure mode and observation period. In practice, the data of identical or closely similar CCF groups of the same size are often pooled together. In a general case, the analysis may include CCCGs of varying size from different systems and/or plants. Steps 5-6 concern the actual impact vector construction and the integration of the impact vectors for the estimation of reliability and dependence parameters.

The impact vector presentation is related to failure modes in a way similar to component and CCF models. Different functional failure modes each require a specific way of treatment. Especially, latent and monitored failure modes should be kept strictly separated because they differ significantly both regarding qualitative analysis and quantitative treatment.

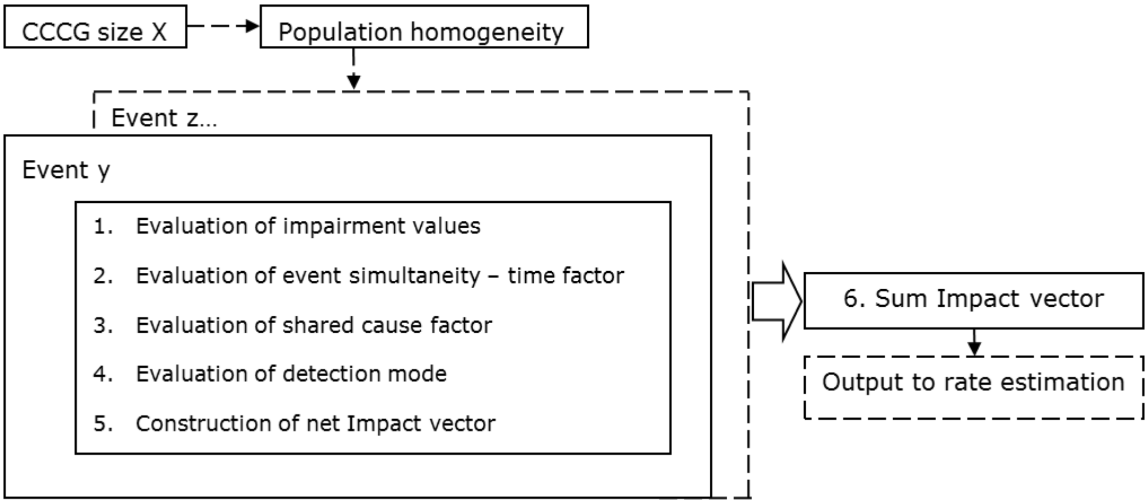

Fig. 3. Procedure for construction of event impact vectors.

II.C.2. *Merging of Impact vectors*

Before any of the impact vectors are used, it must be concluded which component groups and which events to be grouped for the purpose of quantification. It must be assured that the quantification is made on a homogenous set of data. This means that the data set should be divided based on homogeneity issues, but only to such extent that the data set do not become to scarce. Potential basis for grouping are:

- Group size
- Failure modes (e.g. failure to start or failure to run)
- Operating modes (e.g. operational or standby components)
- System types (e.g. clean or raw water centrifugal pumps)

II.D. Parameter estimation

Based on the outcome of the impact vector construction the CCF parameter can be estimated. The estimation procedure used here is "direct estimation" of the failure rate. An algorithm for Empirical Bayesian parameter estimation is applied. The Algorithm has been shown to be an applicable method for CCF parameter estimation application. The algorithm has been applied to derive the uncertainty bounds with parameters representing quantitative uncertainties.

The PREB (Parametric Robust Empirical Bayes) estimation method is designed for estimating failure rates (frequencies), initiating event rates and failure probabilities per demand (opportunity), when failure or degradation event data is available from one or more units (components, systems or plants). The output of the estimation are k out of n specific CCF rates. The CCF rates, *Reg(k|n)*, represents the basic CCF event, *"failing exactly specific k components i, j,… out of n similar components"*.

II.E. Transformation of rates into probabilities and alpha factors

For further treatment of the quantification results (to obtain other parameter such as probabilities, alpha factors, etc.) consideration of test policy, test interval, success criterion for the target plant and system must be made.

The estimated CCF rates can be transformed into probabilities. The probabilities *Peg(k|n)*, representing the basic CCF event; "*failing exactly specific k components i, j… out of n similar components*". For standby safety components, tested with test interval T, the probabilities are:

$Peg(k|n) = \lambda_{(s)\,k/n}\,[c_{k/n}T/2] = Reg(k|n) \times [c_{k/n}T/2]$, where $c_{k/n}$ is the expected residence time coefficient and Reg(k|n) or $\lambda_{(s)\,k/n}$ is the estimated CCF rate.

The expected residence time coefficients $c_{k/n}$ are based on the expected residence times of a CCF in a system, Ref. 2. The coefficients $c_{k/n}$ depend on k, n, test policy, repair policy and the system success criterion. The impact of the difference between simultaneous and staggered testing on the expected residence time coefficient is illustrated in Fig. 4.

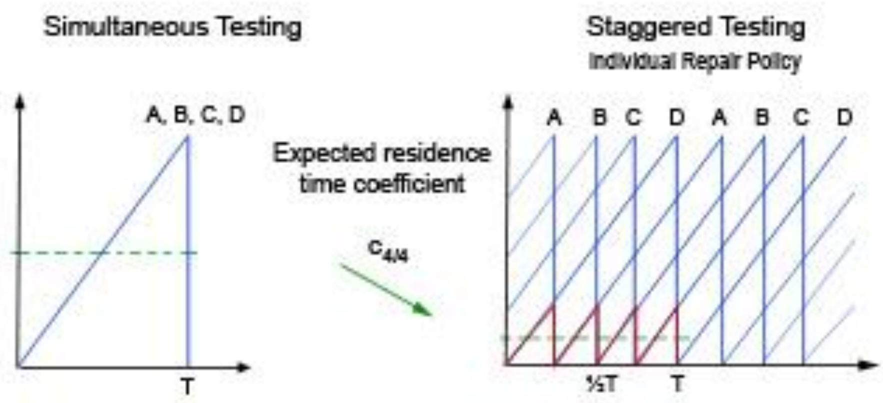

Fig. 4. Sequential testing vs. staggered testing.

The alpha factors represent the fraction of multiple failure events of order k with respect to the total number of failure events. To obtain alpha factors that consider test and repair policies, different test intervals and success criteria, a different formalism is required. For standby components with non-staggered testing scheme, the alpha factors are approximated with Eq. 1:

$$\alpha(m|n) = \frac{\binom{n}{m}Q(m|n)}{\sum_{k=1}^{n}\binom{n}{k}Q(k|n)} = \frac{\binom{n}{m}Peg(m|n)}{\sum_{k=1}^{n}\binom{n}{k}Peg(k|n)} \quad (1)$$

If the testing model is staggered, this has to be considered either by modifying the Common Cause Basic Event probability, Q(m|n), as is done here by choice of $c_{k/n}$, or otherwise by modifying the way the alpha factors are calculated.

It is important to note that when deriving the alpha factors, is either the generic single failure rate or the plant-specific single failure rate used as denominator. Thus, the use of alpha factors is dependent on the single failure rate and the CCF rates.

III. GENERIC CCF RELIABILITY DATA

The scope of the generic CCF reliability data tables (include CCF rates, probabilities for a given test interval, and alpha factors) in the C-book is presented in TABLE III. The components diesels, centrifugal pumps, check valves, motor operated valves and level measurements include data from the Nordic countries (Sweden and Finland) and Germany. Due to the scarcity of data for the components batteries and breakers, the Nordic and German data is supplemented with data from other ICDE member countries. As seen in the table, different conditions of grouping have been used to create as homogenous sets as possible. For instance, the centrifugal pumps are divided depending on system type and operational mode for different group sizes and failure modes. For level measurements and breakers, the formalism for mapping down in Ref. 10 have been applied for mapping down event impact vectors from group size 6 to size 4.

TABLE III. Scope of generic CCF reliability tables in the C-book

Component type	Failure mode	Group Size	System type
Diesels	Failure to Start	Size 2, 3 and 4	-
	Failure to Run		
Centrifugal pumps	Failure to Start	Size 2 and 3	Clean and Raw water pumps (pooled)
		Size 4	Clean water pumps Raw water pumps Clean and Raw water pumps (pooled)
	Failure to Run (operational/intermittent)	Size 2	Clean and Raw water pumps (pooled)
		Size 4	Clean water pumps Raw water pumps Clean and Raw water pumps (pooled)
Check valves	Failure to Close and Failure to remain closed or internal leakage (pooled)	Size 2, 3 and 4	-
Motor operated valves	Failure to Open	Size 2, 4	-
	Failure to Close	Size 4	
Level measurements	Failure to Function	Size 4	-
		Size 4 mapped down from size 6	
		Size 4 mapped down from size 6 and pooled with size 4	
Batteries	Failure to Start and Failure to Run (pooled)	Size 2 and 4	-
Breakers	Failure to Change Position (Open or Close)	Size 4	-
		Size 4 mapped down from size 6	
		Size 4 mapped down from size 6 and pooled with size 4	
	Spurious Operation	Size 4 mapped down from size 6	

An example of the data tables in the C-book is presented in TABLE IV.

TABLE IV. CCF rates, Failure Mode: Failure to start (FS), Single failure rate (T-book 8: 7.3.2)

Group size	C-book ID*	Mean	5th%	50th%	95th%	Dist. Par. 1	Dist. Par. 2
N	Reg(1|N)	1,31E-05	5,00E-07	8,62E-06	3,00E-05	-	-
2	Reg(2|2)	6,74E-07	2,65E-09	3,07E-07	2,59E-06	5,000E-01	1,348E-06
3	Reg(2|3)	3,37E-06	1,32E-08	1,53E-06	1,29E-05	5,000E-01	6,736E-06
	Reg(3|3)	1,02E-05	4,08E-08	4,66E-06	3,92E-05	5,013E-01	2,039E-05
4	Reg(2|4)	1,40E-07	9,14E-17	3,46E-09	7,88E-07	1,320E-01	1,061E-06
	Reg(3|4)	3,87E-08	1,17E-10	1,69E-08	1,51E-07	4,762E-01	8,135E-08
	Reg(4|4)	1,66E-07	5,10E-12	3,23E-08	7,91E-07	2,642E-01	6,286E-07

*Reg(k|n) represents "*failing exactly specific k components i, j,.. out of n similar components*".

IV. QUANTITATIVE APPLICATION – VALIDATION

The aim of the quantitative application is to validate the quantitative results with RiskSpectrums CCF models, specifically the Alpha-4 Factor model and the Alpha-4 Staggered model. In RiskSpectrum, there are two different Alpha-factor models to use depending on system test policy (non-staggered or staggered testing). For the validation, a four train diesel system is used. Four cases with different models with different strategies for testing and repair, and success criteria are studied.

The validation shows that the alpha factors for simultaneous testing can be used in RiskSpectrums Alpha-4 staggered model, under the condition that the repair policy is group repair[a]. The introduction of the new CCF model "Alpha-4 Staggered" in RiskSpectrum results in one very important aspect to consider:

- If RiskSpectrum CCF model "Alpha-4 Staggered" is used, alpha factors for simultaneous testing shall be applied. Otherwise, the effect of staggered testing is counted twice.
- If "modified" alpha factors are used (i.e. factors where the effect of staggered testing, via the expected residence time coefficients, is included), the CCF model "Alpha-4 Factor" shall be applied.

It is up to the user to select which alpha factors to use in the application. Independent of method (direct estimate or alpha factor) the expected residence time of a CCF must be considered to reflect the test and repair policies in a system analysis case. The effect of the expected residence time coefficient regarding individual repair policy versus group repair policy shall not be overlooked. However, individual repair policy may not be relevant so often since group repair is generally assumed for CCF groups.

The validation shows that the CCF data can be applied in RiskSpectrum. It also shows that it is possible to use sequential alpha factors with RiskSpectrums Alpha factor models to take into account the effect of different test policies. However, the results are less conservative compared to if modified alpha factors are used. This is due to that different formalisms are used, i.e. expected residence time coefficients versus the alpha factor formalism in RiskSpectrum. The recommendation is that modified alpha factors shall be used with the CCF model "Alpha-4 Factor". Still, it would be more desirable only to use failure rates combined with test and repair policies as basic parameters.

V. SUMMARY AND CONCLUSIONS

The C-book presents CCF rates for k out of n failures. The reliability data is complemented with CCF probabilities and alpha factors through a basis for transformation of rates into probabilities and/or alpha factors. The quantification methodology comprise of a comprehensive procedure including all steps from CCF event input data, via event impact vectors, to final CCF parameters, which has been developed and validated. The basis for transformation of the quantification results (to obtain other parameter such as probabilities, alpha factors, etc.) allows consideration of test policy, repair policy, test interval, success criterion for the target plant and system. The quantitative application presents the validation of the quantitative results with RiskSpectrums CCF models. The validation demonstrates that the CCF rates can be applied and used. The development of a CCF data book, which contains generic and plant specific CCF rates, probabilities and alpha factors, will improve the quality of data for the dependency analysis in the PSA for nuclear power plants.

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[a] I.e. when one component is found failed, all components of a group are checked and repaired if failures are detected.