

Research

Dependency Analysis Guidance

Nordic/German Working Group on Common cause
Failure analysis.

Phase 1 project report: Comparisons and application
to test cases

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SKI-perspektiv

Bakgrund

SKI ställer krav på PSA-studier och PSA-verksamhet i SKIFS 2004:1. Uppföljning av denna verksamhet ingår därför i SKI:s tillsynsverksamhet. Enligt krav i SKIFS 2004:1 skall säkerhetsanalyserna vara grundade på en systematisk inventering av sådana händelser, händelseförlopp och förhållanden vilka kan leda till en radiologisk olycka.

Forskningsrapporten *“Nordic/German Working Group on Common cause Failure analysis. Phase 1 project report: Comparisons and application to test cases”* har utvecklats på uppdrag av Nordiska PSA-gruppen (NPSAG) tillsammans med sin tyska motsvarighet, VGB, med syftet att skapa en gemensam erfarenhetsbas för försvar och analys av beroende fel, s.k. Common Cause Failures (CCF).

SKI:s och rapportens syfte

Ordet vägledning (Guidance) i rapporttiteln används för att tydliggöra en gemensam metodologisk och av NPSAG accepterad vägledning som baserar sig på den allra senaste kunskapen om analys av beroende fel och anpassade till förhållanden som anses gälla för nordiska kärnkraftverk. Detta kommer att göra det möjligt för tillståndshavarna att genomföra kostnadseffektiva förbättringar och analyser.

Resultat

Rapporten *“Nordic/German Working Group on Common cause Failure analysis. Phase 1 project report: Comparisons and application to test cases”* presenterar ett gemensamt försök, mellan myndighet och tillståndshavare, att skapa en metodologi och erfarenhetsbas för försvar och analys av beroendefel.

Den benchmark som har genomförts visar hur viktig tolkningen av data är för resultatet. Bra egenskaper har identifierats i samtliga tillvägagångssätt. Dessa erfarenheter bör vi använda till att utveckla ett harmoniserat tillvägagångssätt. Nästa steg kan vara att utveckla händelse och formel styrd generering av *“impact vectors”* baserat komponent påverkan, tidsskillnader och värdering av gemensam orsak. Efter slutförandet av fas 1 har beslut fattats att arbetet ska fortsätta med en andra fas. Målsättningen med fas 2 ska vara att utveckla en gemensam procedur och modell för kvantifiering av CCF händelser.

Eventuell fortsatt verksamhet inom området

Erfarenheter från tillämpningen av rapportens vägledningar skall inväntas, eventuella större ändringar i vägledningsdokumentet beslutas om vid senare tillfälle. Utveckling av metoder och förfining av sådana pågår dock, vartefter det ställs högre krav på nya analysförutsättningar och -djup. SKI uppmanar tillståndshavarna, organisationer och andra, som behöver ha tillgång till harmoniserad CCF-data, att fortsätta att kämpa vidare med svårigheterna att skapa robusta beroendefelsdata, med andra internationella organisationer.

Effekt på SKI:s verksamhet

SKI Rapport 2007:41 "Nordic/German Working Group on Common cause Failure analysis. Phase 1 project report: "Comparisons and application to test cases" bedöms även ge ett bra stöd för myndigheterna i sin granskning av olika tillståndshavares verksamhetsprocesser, analysmetoder förknippade med analyser av beroende fel.

Projektinformation

SKI:s projekthandläggare: Ralph Nyman

Projektnummer: 2006 02 011

Dossié-diarienummer: SKI 2006/949

Annat: Denna rapport, kommer också att utges som en unik rapport i VGB:s egen rapportserie.

SKI-perspective

Background

The Swedish Nuclear Inspectorate (SKI) Regulatory Code SKIFS 2004:1 includes requirements regarding the performance of probabilistic safety assessments (PSA), as well as PSA activities in general. Therefore, the follow-up of these activities is part of the inspection tasks of SKI. According to SKIFS 2004:1, the safety analyses shall be based on a systematic identification and evaluation of such events, event sequences and other conditions which may lead to a radiological accident. The research report *“Nordic/German Working Group on Common cause Failure analysis. Phase 1 project report: Comparisons and application to test cases”* has been developed under a contract with the Nordic PSA Group (NPSAG) and its German counterpart VGB, with the aim to create a common experience base for defence and analysis of dependent failures i.e. Common Cause Failures CCF.

The aim of SKI and the Report

The word Guidance in the report title is used in order to indicate a common methodological guidance accepted by the NPSAG, based on current state of the art concerning the analysis of dependent failures and adapted to conditions relevant for Nordic sites. This will make it possible for the utilities to perform cost effective improvements and analyses.

Results

The report *“Nordic/German Working Group on Common cause Failure analysis. Phase 1 project report: Comparisons and application to test cases”* presents a common attempt by the authorities and the utilities to create a methodology and experience base for defence and analysis of dependent failures. The performed benchmark application has shown that how the data is interpreted is of significant importance. Good features were found in all approaches. We should try to take them and develop the existing approaches into a harmonised direction. A next step could be to develop and agree on event & formula driven impact vector creation based on component impairments, time differences and shared cause assessment. Following the conclusions of phase 1 it was decided to proceed with a second phase of the project. The objectives for phase 2 will be to establish a common procedure and model of quantification for CCF events.

Possible Continued Activities within the Area

Experiences from the application of the Guidance shall be awaited for, i.e., major changes or extensions to the document shall be decided at a later stage. However, the development of methods is an on-going process which is guided by changes in analysis assumptions or increased level of detailed of the analysis. SKI encourages licensees, organisations and other, who need best available and harmonized CCF-data, to contend with the difficulties to get robust dependency data, with other countries.

Effect on SKI activities

The SKI Report 2007:41 - "Nordic/German Working Group on Common cause Failure analysis. Phase 1 project report: Comparisons and application to test cases" is judged to give useful in supporting the authority's review of procedural and organizational processes at utilities, methodology for the analysis of dependent failures.

Project information

Project responsible at SKI: Ralph Nyman

Project number: 2006 02 011

Dossier Number: SKI 2006/949

Other: This report will also be published as an unique VGB report and with an unique VBG report number.

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October 2007

This report concerns a study which has been conducted for the Swedish Nuclear Power Inspectorate (SKI). The conclusions and viewpoints presented in the report are those of the author/authors and do not necessarily coincide with those of the SKI.

Sammanfattning

Denna rapport utgör en del av rapporteringen från the European Working Group on CCF analysis (EWG). Gruppen inkluderar projektmedlemmar från Finland, Tyskland och Sverige. Rapporten presenterar en sammanfattning av de jämförelser och tillämpningar på testfall som utförts under projektets första fas.

Summary

This report is part of the reporting from the European Working Group on CCF analysis (EWG), including members from Finland, Germany and Sweden. The report provides a summary on performed comparisons and application to test cases during the first phase of the project.

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List of acronyms

CCCG	Common Cause Component Group
DG	Diesel Generator
EPRI	Electric Power Research Institute
EWG	European Working Group on CCF analysis
Fi	Finnish
Ge	German
ICDE	International Common Cause Data Exchange
NAFCS	Nordisk Arbetsgrupp för CCF studier
Nr	Nordic
PREB	Parametric Robust Empirical Bayes method
Se	Swedish
TDC	Test and Demand Cycle

1 Introduction

This report is part of the reporting from the European Working Group on CCF analysis (EWG), including members from Finland, Germany and Sweden.

The project is planned in two phases with a reporting and progress evaluation before initiation of the second phase.

Phase 1: Comparisons and application to test cases (2006)

Phase 2: Development of harmonized approach and applications (2007)

This report summarizes the work during the 1st phase of the project, which included the following main tasks:

- Task 1: Survey of databases,
- Task 2: Survey of methods for classification and quantification of CCF-events and description of these methods.
- Task 3: Classify events for application, using different approaches as recommended above.
- Task 4: Draw conclusions for harmonization.

2 Project background

Participants of this project have been nuclear utilities in Germany and in the Nordic countries, which are constituted by Sweden and Finland. Nordic countries have been represented by NPSAG, German utilities have been represented by VGB.

A large variety of CCF-models have been developed and suggested in the past. (A short review is provided in PROSOL 7001, enclosure 14.) Due to lack and scarcity of CCF event data, parameters of the models have been largely judgmental and subjective. Earlier CCF-specific data collection efforts (EPRI, NRC) are somewhat outdated and applicability to other (European) plant designs is questionable. More details on the events and at which plants they occurred may not be available, except through ICDE. ICDE is the first extensive international effort that has potential to provide a sufficient empirical data base for CCF quantification for a large variety of systems and components. This can lead to less subjective and more plant-specific (rather than average) numerical values, which is important when making serious plant-specific risk-informed decisions concerning safety of NPP.

Both in Germany and Nordic countries, there have been national projects on CCF: In the Nordic countries, the NAFCS project, and in Germany, VGB had GRS collect CCF data in a specific database. Both projects led to interesting results, but also showed deficits of purely national projects. The NAFCS project had very promising results for Diesels, but concerning centrifugal pumps it turned out, that for other CCF Groups, there are too few events. Hence, there has been an interest to have additional raw events and corresponding contacts to the respective plants. The VGB project showed results for

high failure-multiplicities that appear to be quite large in the utilities' view. So, there has been an interest to systematically compare the quantification approaches, making use of international experts.

3 Program

3.1 Objectives

The objectives for the project were formulated at a preproject meeting in early 2006.

Phase 1 objectives:

- suggest and test co-operation procedures,
- carry out applications to test cases,
- perform comparisons of existing approaches (in participating countries),
- benchmark exercises (using different existing approaches),
- identify sources of uncertainties in data assessment (in terms of models and completeness).

Phase 2 objectives are tentatively formulated and may be reformulated based on the results from phase 1:

- provide a common basis for methods and guidelines for data classification and assessment,
- improve consistency in international in-depth assessment of CCF events for parameter assessment,
- provide interpretation of raw data for exchange and use in CCF models.

3.2 Definition of phase 1 project activities

The main activities in phase 1 were organized in 4 tasks as defined during the preparation meeting. (ES-konsult PM 2006-05-03 European Working Group For assessment of CCF, Minutes EWG CCF 20060607):

Task 1: Survey of databases used in Sweden, Finland and Germany. Includes assessment of data in ICDE, GRS-data, NAFCS-data, Finnish data, and possibly other sources. Report on the categorization scheme, level of detail of textual description, amount of data (number of events and plant years), examples of event descriptions, type of data (raw data versus processed data).

Task 2: Survey of methods for classification and quantification of CCF events and description of these methods. Report on how data is processed qualitatively and quantitatively to obtain single CCF event assessment. Description of how events are selected for population and for quantification, how they are combined, and how CCF rates are quantified (including uncertainty quantification). Comparison of CCF-data (German PSA guideline, NAFCS, EPRI, NUREG etc.) on diesel units and centrifugal pumps. Recommendation for subsequent evaluation of methods.

Task 3: Classification of events for application, using different approaches as recommended above. The focus will be on size four component groups (diesel units and centrifugal pumps). Development of CCF-rates based on the different approaches. Explanation of differences. Assessment of the validity of the important model features.

Task 4: Drawing of conclusions for harmonization. Assessment of possibilities or needs for common guides. Documentation of phase 1 outcome in a summary report.

3.3 Outputs

The following reports represent the project Phase 1 outputs and form the basis for this summary report:

Data evaluation guidelines and surveys

1. ES konsult: Survey of Swedish CCF Methodology. 2006018_001 1.0
2. ES konsult: Data Survey. 2006018_002 1.0
3. Fortum: Fortum CCF Methodology
4. RISA123-07_Survey_German_Database
5. RISA124-07_Survey_PEAK_CCF_method

Data test evaluation applications

6. ES konsult: Evaluation of German diesel data. 2006018_003 1.0¹
7. ES konsult: Evaluation of German pump data. 2006018_004 1.0²
8. ES konsult: Assessment results for Nordic and German CCF data. 2006018_005 1.0
9. Fortum: CCF Benchmark.
10. Fortum: CCF2006-L-Diesel_VN.doc
11. Fortum: CCF2006-L-Pump_VN1.doc
12. RISA125-07_German_Benchmark_Results
13. ES konsult: Harmonized data set for emergency diesel generators and centrifugal pumps. 2006018_007 1.0

Documents on comparisons of approaches

14. Vaurio: PROSOL-7001_JKV-ESKonsult-NPSAG_Rev1.doc
15. Vaurio: PROSOL-7002_JKV-ESKonsult-NPSAG-Review_German_Meth_Final.doc
16. ES konsult: Thesis report. 2006018_006 1.0
17. RISA GB: Note on convergence of PEAK
18. Impact Vector example Note JKV 2007-04-13

¹ For Nordic diesel data evaluation see NAFCS, PR10: Impact Vector Application to Diesels.

² For Nordic pump data evaluation see NAFCS, PR18: Impact Vector Application to Pumps

4 Databases and data

4.1 Data Survey

The purpose of this survey, which summarizes the outputs 2 and 4 (see section 3.3 above) is to give an overview of the existing German and Nordic CCF data.

4.1.1 General statistics

The only data source used in Sweden is the ICDE Database. In Finland, at Fortum, the ICDE Database is also used. This data has been supplemented by older American data sources (EPRI and NRC), which were originally (1989...2000) the only data sources at Fortum in addition to their own plant data. These older American data sources are not useful in this EWG project. In Germany the GRS database for Common Cause Failures is used. This is a database that includes German and international experience data, where a subset is constituted by ICDE data.

The ICDE Project covers the key components of the main safety systems. Presently, the components listed below are included in the ICDE Project.

- Centrifugal pumps
- Diesel generators
- Motor operated valves
- Safety relief valves/power operated relief valves
- Check valves
- Batteries
- Level measurement
- Breakers
- Control rod drive assemblies
- Heat exchangers

This report will focus on centrifugal pumps and emergency diesel generators.

Some general statistics are presented in Table 1.

Component	Data	Country			Total
		Finland	Germany	Sweden	
Battery	Start	1982-01-01	1995-01-01	1986-01-01	1982-01-01
	End	1995-12-31	2000-12-31	2002-12-31	2002-12-31
	Sum of Groups	8	11	22	41
	Sum of Events	1	8	0	9
Breakers	Start	1983-01-01	1997-01-01	1986-01-01	1983-01-01
	End	2004-12-31	2002-12-31	2002-12-31	2004-12-31
	Sum of Groups	44	23	48	115
	Sum of Events	2	5	1	8
Centrifugal	Start	1977-05-01	1990-01-01	1986-01-01	1977-05-01
	End	1996-12-31	1994-12-31	2003-12-31	2003-12-31
	Sum of Groups	22	136	91	249
	Sum of Events	2	5	15	22
Check valves	Start	1985-01-01	1990-01-01	1975-01-01	1975-01-01
	End	2000-12-31	1999-12-31	2003-12-31	2003-12-31
	Sum of Groups	16	337	95	448
	Sum of Events	0	14	5	19
Control Rod Drive Assembly	Start	1983-01-01	1997-01-01	1983-01-01	1983-01-01
	End	2003-12-31	2003-12-31	2003-12-31	2003-12-31
	Sum of Groups	2	59	9	70
	Sum of Events	5	1	22	28
Diesels	Start	1977-05-08	1994-01-01	1986-01-01	1977-05-08
	End	1997-12-31	1998-12-31	2003-12-31	2003-12-31
	Sum of Groups	6	38	14	58
	Sum of Events	14	9	17	40
Level	Start	1983-01-01	1994-01-01	1990-01-01	1983-01-01
	End	2001-12-31	1998-12-31	2003-12-31	2003-12-31
	Sum of Groups	10	52	105	167
	Sum of Events	0	7	9	16
Motor Operated Valves	Start	1983-01-01	1990-01-01	1980-01-01	1980-01-01
	End	1997-12-31	1994-12-31	2003-12-31	2003-12-31
	Sum of Groups	2	5	105	112
	Sum of Events	1	6	7	14
Safety and Relief Valves	Start	1977-05-08	1994-01-01	1980-01-01	1977-05-08
	End	2000-04-30	1998-12-31	2003-12-31	2003-12-31
	Sum of Groups	16	99	40	155
	Sum of Events	12	10	26	48
Total Min of Start		1977-05-01	1990-01-01	1975-01-01	1975-01-01
Total Max of End		2004-12-31	2003-12-31	2003-12-31	2004-12-31
Total Sum of Groups		126	760	529	1415
Total Sum of Events		37	65	102	204

Table 1. Component group statistics per country registered in the ICDE database.

4.2 Data processing

The ICDE format has been used as the definition of raw data. The data base description task has been to describe the differences from the ICDE format.

Information needed to be entered into the ICDE database include the following: plant name, plant type, component type, design information, PSA failure mode, number of impaired components, cause of failures or degradations, timing of the impairments, how the impairments were detected, how the impairments were linked together, shared cause factor, the strength of the root cause of failure, and the timing of the events (timing factor). An event description is also needed, as well as a rationale for the coding of the

fields if it is not obvious from the event description. Details of the above fields can be found in the ICDE General Coding Guidelines [3].

As an example consider the impairment of the components. Components are classified according the following coding scheme:

- Complete failure of the component to perform its function
- Degraded ability of the component to perform its function
- Incipient failure of the component
- Component is working according to specification (default).

The event description is a narrative of the event. It should include the following:

- System operating on demand, system in standby
- Influences or causes introduced by test and maintenance activities or by external events
- Method of discovery
- Any special circumstances, environmental conditions
- Operational state of the plant at the time the event was discovered. The power field contains the power level at the time of the CCF event as a percentage of full power.
- Description of the observed damage to the component
- Characterization of the condition that is readily identifiable as leading to the failure
- Description of causes
- Conditioning event
- Trigger event

The processed information is the additional information added to the data when evaluating the data base to derive qualitative or quantitative information. Evaluations done based on the processed information are described in the survey. In addition to the ICDE data, the German data base includes the application factors that have been entered as a part of the post processing of the ICDE information. Time factor and shared cause factor are missing in most cases, as the German evaluation code makes no use of these. In the case of Finland and Sweden no additional information has been added.

4.3 Harmonized data

The data set considered for emergency diesel generators and centrifugal pumps originates from the ICDE database, GRS data, and Finnish (Fortum) data. A cooperative analysis of each event has constituted the basis for conclusion on which data points are relevant and therefore to be included, and which are not. A summary of concluded data set is presented in ES konsult 2006018_007 1.0. See chapter 6, Benchmark application, for further details on harmonization issues.

4.4 Discussion

The structure of the databases used is not identical but quite similar among the partners. All databases strongly resemble the ICDE layout.

Germany and Finland use some information not contained in ICDE. In case of Germany, this is the applicability factor. This factor tries to model the difference between source component-group (where the event occurred) and target component-group (for which a CCF value is to be determined). So, this value does not fit into the philosophy of ICDE, which focuses on collection of events rather than evaluations. In Finland, they observed, that it is frequently difficult to assess a single shared cause respective timing factor for an event. They assess different values for different numbers of failed components, as in practice, there are e.g. cases, where two components fail one shortly after the other, whereas a third one clearly is damaged a long time after the first two. As this information is related to events, it could be stored in ICDE (although this would require a change in the ICDE data base structure).

5 Methods

Methodology description has been given in the output reports 1, 3, and 5 (see section 3.3 above). Summary of these reports are provided below.

5.1 Survey of methods

The purpose of this survey is to give an overview of the methods used in German and Nordic CCF data analysis. It has been attempted by all partners to use the structure given below.

Survey of CCF method
Introduction (Provide brief information on the model; possibly giving relations to other related models.)
Description of CCF Method
Basic assumptions and reasoning (What is the main idea behind the model?)
Definition of input information required (Description of inputs including symbols used subsequently)
Mathematical implementation (Exact formulation of the model)
Treatment of uncertainties (How is uncertainty dealt with)
Usage of the CCF Method (What processed information is stored for an event?)
Processing of raw data (How is expert assessment converted into model parameters?)
Up scaling and down scaling (What help is given concerning different group sizes in target plants?)
Example (Simple numerical example to show, how it works)
Summary

Table 2. *Structure of method survey.*

A survey has been performed and is presented in

- Kabranis RISA123-07_Survey_German_Database
- Jänkälä Fortum: Fortum CCF Methodology
- Jonsson ES konsult: Survey of Swedish CCF Methodology. 2006018_001 0.3

This section provides an extended summary of the three CCF quantification methods covered in the project. The chapter also includes a discussion of specific features and key parameters of the various methods, and a comparative overview.

The methods are referred to as the PEAK method (developed by GRS, Germany), the Fortum method (developed by Fortum Nuclear Power, Finland), and the NAFCS method (developed within the Nordic NAFCS project). Each of the methods is described in detail in separate documents.

5.2 The PEAK Method (germany)

5.2.1 General summary

The PEAK method has been developed by GRS, and was used to calculate the generic CCF data in the German PSA procedures guide (Leitfaden) [1]. It is described in [2].

Basic model

The method is based on a binomial failure rate (BFR) model, i.e., a multiple parameter shock model. It estimates the frequency of multiple components failures by assuming that the system is subject to common cause shocks at a certain rate and estimating the conditional probability of failure of components within the system, given the occurrence of shocks. This conditional probability of multiple failures is also referred to as the coupling parameter p .

Thus, in the BFR model, the CCF failure rate of a K out of N system is given by:

$$\lambda_{BFR} = \lambda_s \sum_{i=K}^N \binom{N}{i} p^i (1-p)^{N-i}$$

Where,

λ_s	The rate of the CCF shocks
p	The coupling parameter, i.e., the conditional probability of failure given a CCF shock

Adaptation to specific failure data and plants

The impact of a shock on a specific group of components is assumed to vary significantly due to the diversity of the different CCF phenomena and the special characteristics of the group. As a consequence, for each observed CCF phenomenon, the coupling factor linked to the specific shock can also vary significantly.

For these reasons, each observed CCF event is handled separately in the PEAK model, i.e., for each CCF event, a specific coupling factor p is estimated. The factor which is related to the observed CCF phenomenon for the specific group.

A separate estimation of the coupling parameter p_j is performed for each observed CCF event j . Applying parameter p_j to the specific group of r components to be evaluated, the proportional part $P_{j;k/r}$, $k = 0, \dots, r$ of the CCF probabilities contributed by the corresponding CCF event j is calculated for each failure combination k -out-of- r failures by:

$$P_{j;k/r} = \frac{T_{CCFj}}{T_{obs}} \cdot f_j \cdot \binom{r}{k} p_j^k (1-p_j)^{r-k}$$

Where,

r	the number of components in the specific group
k	the number of failed components due to the shock
p_j	the coupling factor
T_{CCFj}	the failure detection time
T_{obs}	the population observation time
f_j	the applicability factor.

The term $\frac{T_{CCFj}}{T_{obs}} \cdot f_j$ can be interpreted as an estimation of probability per demand of a

specific CCF phenomenon j for the considered component group.

Summing up all CCF probabilities over all relevant CCF events, results in the following estimation of the total CCF probability of a k-out-of-r failure:

$$P_{k/r} = \sum_{j=1}^N P_{j;k/r},$$

Where,

N	the number or relevant CCF events in the regarded event collection.
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5.2.2 Specific features and key parameters

Population Observation Time T_{obs}

This is the sum of the observation times of all component groups that constitute the population.

See comment in connection with application factor f_j

Failure Detection Time T_{CCFj}

The failure detection time for a component group is determined by its maintenance strategy or its operating mode. For standby components the detection time is determined by the inspection intervals of the components in the group.

In case of staggered testing, the following holds.: If after the detection of a single failure, the rest of the group of redundant components is tested, then the failure detection time is considered equal to the time between two consecutive tests. If the other components are not tested, this time interval is doubled. If no staggered testing policy is applied, then the failure detection time equals the total group inspection period.

Further details on the consideration of T_{CCFj} are given in the detailed method description.

This procedure results in high unavailability values for CCF events with high multiplicity in case of staggered testing without a rule to test the rest of the group. When the first failure is found the component is repaired usually well before the next test. After the repair it is available again leading to the fact that a complete CCF cannot exist longer than the time between proper successive tests.

Coupling Parameter p_j

In most cases, the coupling parameter for a CCF event j is estimated on the basis of the default proposition of the impact vector w , which is directly derived from the degradation vector. It is subsequently used for calculating the CCF probabilities without projecting the estimated coupling parameter separately onto the specific component group.

The procedure results in the “automatic” assignment of rather high probabilities for CCF events with high multiplicity.

Applicability Factor f_j

In general, CCF events of a CCCG belonging to one of the pre-defined populations of CCFG:s are supposed to be fully applicable to other CCCG:s of the specified population.

However, for some CCF phenomena, an unrestricted application of the observed CCF event to all CCCG:s is judged to be inadequate³. In this case, engineering judgment is necessary to decide whether or not a specific observed CCF phenomenon that has appeared in the source group can appear with a less, equal or higher probability in a specific target group.

The quantification of qualitative differences is expressed by the applicability factor f_j , which expresses the conditional probability of occurrence of CCF phenomenon j in the specific target group relative to the probability of occurrence in the source component group.

In some cases applicability factors lower than 1 were given also for the component group in which the event occurred. In most of these cases the applicability factor can be interpreted as the product of time factor and shared cause factor. Thus, these factors could be determined backwards from the applicability factor.

The procedure and rationale for assigning application factors is not easily understood. There may also be potentially be problems with achieving sufficient consistency of judgement. The severity of this problem is highly dependent on the instructions given to the experts participating in the expert judgement; these instructions have not been reviewed during this project.

Also there is an implicit connection between the applicability factor and the observation time which has not been considered in the PEAK method. Thus, it seems reasonable that low applicability of events that have occurred in a source plant should lead to a reduction of the observation time of that same plant).

³ An example is the distinction made between pumps working with clean or with raw water.

Impact vector generation

The default proposition of the impact vector w is directly derived from the degradation vector (formula driven). Component degradation values are assigned as part of the expert judgement assessment of every CCF event using the subjective degradation values in the table below.

Failure Category	Degradation Value
Failure	1
Strongly Degraded	0.5
Slightly Degraded	0.1
Very Slightly Degraded	0.01
Not degraded	0

Table 3. *Component degradation values.*

As seen, the predefined degradation values are the same as used in the ICDE reporting system, except for the “very slightly degraded” value.

The category “very slightly degraded” does not exist in the ICDE classification system, and seems to be rather frequently used in the German data.

Expert judgement

Expert judgement is extensively used throughout the process, both for assessment of CCF failure multiplicity, component impairment within the CCCG:s, applicability of source events to target CCCG:s, as well as for deriving probability distributions based on spread between assessment made by multiple experts.

A rather large group of experts (6 people) was used for the evaluation and quantification of CCF events presented in the German PSA procedures guide (Leitfaden) [1].

5.3 The Fortum Method (Finland)

5.3.1 General summary

The methodology consists of the

- selection of the data source,
- selection of source plants,
- selection of source systems and component type,
- assessment of the impact vectors,
- calculation of CCF rates with uncertainties using an empirical Bayes estimation method, and
- determining CCF basic event probabilities to be used in the probabilistic safety assessment model.

The common cause failure procedure being implemented at Fortum is presented in the figure below.

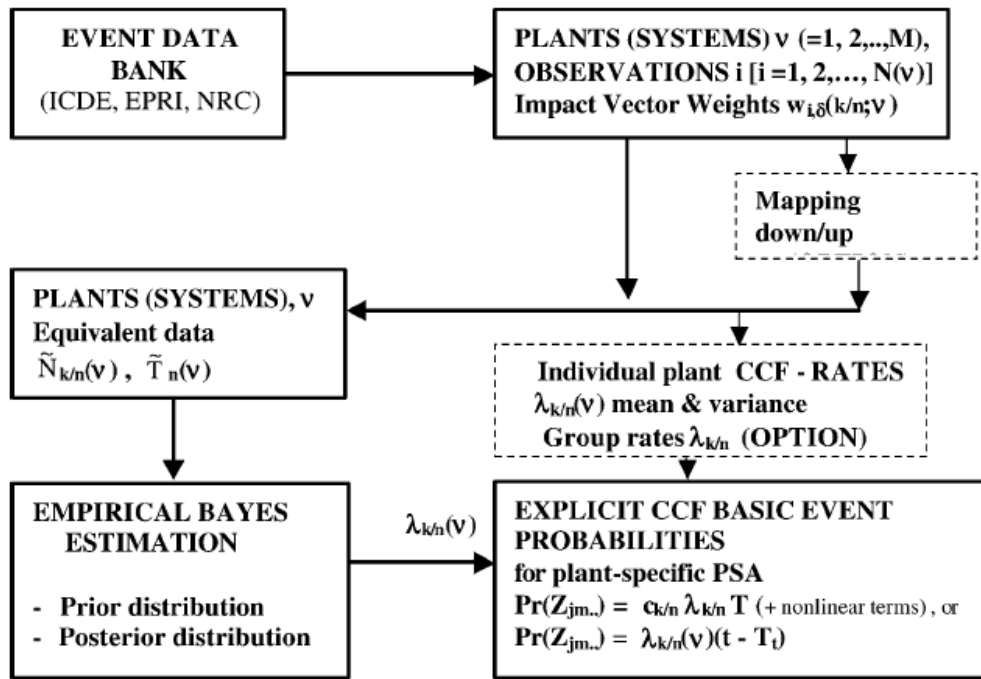


Figure 1. Fortum method procedure.

Generic CCF-event data is taken from EPRI, ICDE, and other sources. In addition, plant-specific events that occurred at the target Loviisa plant have been collected and analysed.

CCF groups are first defined for the target plant (Loviisa NPP). This is followed by the identification (among the generic CCF information available) of relevant source plants. These will be used as the sampling population from which the prior distributions of k/n -event rates $\Lambda_{k/n}$ will be determined. No mapping of data is done, i.e., only data from plants that have the same degree of redundancy (n) as the target plant are used.

The next step is to define the impact vector weights $w_{k/n}(i,v)$ for each plant v for each observation i . for $k = 1,2,\dots,n$. Assessing and quantification of impact vector weights are based on component degradations, shared causes and timing (simultaneity). The method is slightly modified from NUREG/CR-6268, Vol. 2. A multi-step procedure is applied in which a separate estimation is made for each failure multiplicity (k), considering component impairment (classified according to ICDE), the shared cause factor p_s and the time factor t_s . The procedure includes the possibility (usually not needed) to define and evaluate several subsets C_s of failure for a specific multiplicity k .

In the final step, plant specific CCF rates $\Lambda_{k/n}(v)$ are determined. This is done with a robust parametric moment matching method that yields the population distribution of the rate $\Lambda_{k/n}$ of k/n -events for the whole plant population. This is the empirical prior distribution used in the Empirical Bayes Estimation (EBE) process. The posterior distribution of $\Lambda_{k/n}(v)$ for the target plant is then obtained, and the distribution of the rate of *specific* k failures out of n , $\lambda_{k/n}(v) = \Lambda_{k/n}(v)/\binom{n}{k}$.

Finally, the rates are transformed to the probabilities $z_{ij..}$ of the basic CCF-events $Z_{ij..}$ (failing exactly specific k components $i, j,..$ out of n similar components) needed in the system fault tree. For standby safety components tested with test interval T these values are

$$\Pr(Z_{ij..}) = c_{k/n} \lambda_{k/n} T, \quad (4)$$

where $0 < c_{k/n} < 1$. The coefficients $c_{k/n}$ depend on k, n , test staggering, repair policy and the system success criterion.

5.3.2 Specific features and key parameters

Shared Cause Factor p_s

A CCF event must result from a single shared cause of impairment. The shared cause factor allows the analyst to express his degree of confidence about the shared cause. Different shared cause factors can be assessed for different failure multiplicities.

Multiple subsets C_s

One event can consist of one or more CCF-events due to different mechanisms.

Time Factor t_s

Factor related to the time between the failures that have occurred in a specific CCF event. A consequence of the multi-stage procedure used for deriving the impact vector is that different time factors can be used in different steps of the same impact vector construction.

5.4 The NAFCS Method (Sweden)

5.4.1 General Summary

The figure below gives an overview of the impact vector construction process as applied in the NAFCS method.

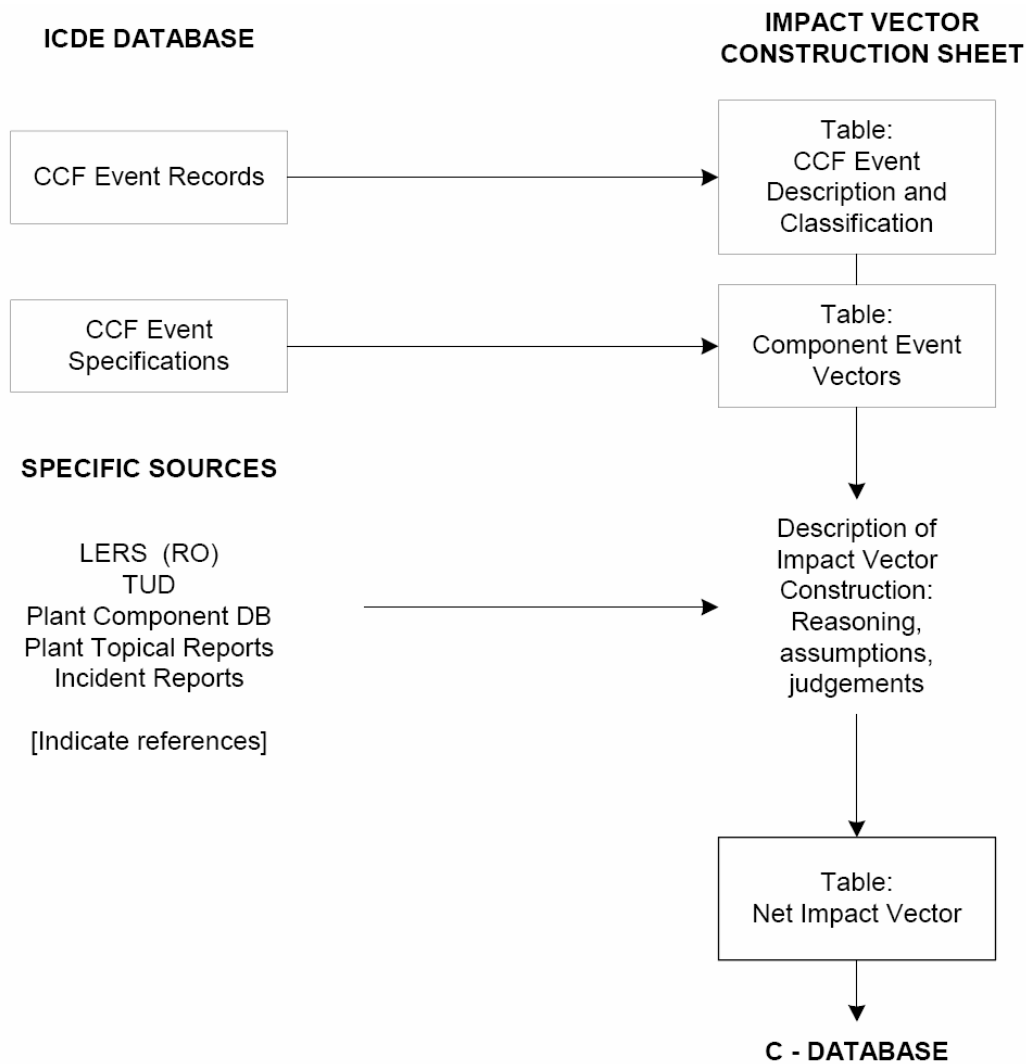


Figure 2. The NAFCS method procedure.

The method is quite straightforward, the basic idea being to construct impact vectors using scenarios. The impact vectors are then used to derive probabilities of CCF events either through direct estimates or by using other methods.

The impact vector provides the analyst with a way to express the spectrum of chances (or equivalently the uncertainty) by a distribution of the possible outcome of an actual demand over different failure states. The principal method for impact vector assessment is the use of alternative scenarios (hypotheses) about the CCF impact, see Table 4.

Scenario		Weight	Impact vector					Element sum
			0	1	2	3	4	
1.	Only DG3 would fail due to fuel fire in demand condition, DG4 would survive	0.8		1				1
2.	Both DG3 and DG4 would fail due to fuel fire in demand condition	0.2			1			1
Net impact vector			0	0.8	0.2	0	0	1

Table 4. Example of Impact Vector construction in a group of four diesel generators, using the scenario method.

The impact vector constitutes an interface between the CCF event analysis and the statistical treatment and quantitative assessment of CCF probability. The parameters of various CCF models can be estimated from the impact vectors of occurred CCF events in an observed component population of a certain component type.

An impact vector expresses the conditional 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. In a group of 'n' components, which is exposed to the CCF, the impact vector contains 'n+1' elements, one for each order of failure 'm', including the outcome 'no failure' ($m = 0$) and 'all failed' ($m = n$). The elements describe the probability distribution for the outcome states of a postulated demand in the presence of the CCF mechanism.

An impact vector is a generalized presentation of the demand outcome. It is especially needed in such situations where the outcome is not perfectly known to be one certain failure state, chances existing for different states. Impact vectors constitute an interface from the CCF event analysis to the statistical treatment and quantitative assessment of CCF probability.

Summing up the Impact Vectors over the Test and Demand Cycles (TDCs) of the observed population produces a Sum Impact Vectors. A Sum Impact Vector represents the failure statistics arranged according to failure multiplicity and constitutes an input to the estimation of parameters for the CCF models.

When constructing the Impact Vectors it may help to make bounding considerations with pessimistic and optimistic assumptions. High and low bound Impact Vectors can be obtained from the component degradation values, d_k , assuming them as independent conditional probability of component failure, together with the Time Factor and the Shared Cause Factor.

5.4.2 Specific features and key parameters

Shared Cause Factor

A 'low' Shared Cause Factor indicates that the events might be independent ones. Due to the possible non-visible dependence though, it is recommended that such events are not excluded. This should at least be applied in a situation where complete non-screened event statistics is available. The Shared Cause Factor is considered when constructing bounding Impact Vectors.

Time Factor

Events with Time Factor equal to 'Zero' should be screened out and placed into a separate analysis category. Events spread out in time are treated somewhat differently, having an affect on scenario identification and how to assign weighting (since joint impact vector covering the concerned TDCs are to be constructed.). The Time Factor is also considered when constructing bounding Impact Vectors.

Scenario definition

There is no one-to-one correspondence between The Impact Vector and the impairment vector, although they are fundamentally connected. If ‘m’ components are completely failed and ‘j’ degraded, the highest order of non-zero elements in the Impact Vector is ‘m+j’. Scenarios are usually defined in a straightforward way with a separate scenario for each possible failure multiplicity. An important feature of this method with large impact on the results, is the assignment of weights to the defined scenarios.

Use of expert judgement

Expert judgement is a crucial part of the method, being extensively used throughout the process, for scenario definition, evaluation of ICDE parameters (such as component impairment vector, time factor and shared cause factor), as well as for assigning weights to identified scenarios. Expert judgement is used to a larger extent than in the other methods as the impact vector weights are not estimated formula-driven but by expert judgement.

5.5 Overview of the methods

The following table is intended to give an initial overview of the methods.

Characteristic	PEAK / Germany	Fortum / Finland	NAFCS / Sweden
Data source	<ul style="list-style-type: none"> • ICDE data (Germany) • Additional national data (not yet in ICDE) • Incident reporting system (IRS) 	<ul style="list-style-type: none"> • EPRI data • ICDE data • Plant specific (Loviisa) 	<ul style="list-style-type: none"> • ICDE data (Sweden / Finland)
Impairment	1 Failed 0,5 Strongly degraded 0,1 Slightly degraded 0,01 Very slightly degr. 0 Not degraded	1 Failed 0,5 Degraded 0,1 Incipient 0 Working	1 Failed 0,5 Degraded 0,1 Incipient 0 Working
Impact vector construction	Formula driven creation based on component impairment vectors.	Event & formula driven creation based on component impairments, time differences and shared cause assessment.	Scenario method; weighing together of set of alternative impact vectors. Impairment information used as part of input.
Mapping up.	Mapping up is done implicitly using binomial model assumption	No mapping up.	No mapping up.
Use of shared cause factor	No	Yes	Yes
Use of time factor	No	1 Same test interval 0,5 1-2 TI 0.1 2-3 TI	Yes

Characteristic	PEAK / Germany	Fortum / Finland	NAFCS / Sweden
Use of applicability factor	Yes	No	No
Use of expert judgement methodology	Extensively used throughout the process, both for assessment of impairment and applicability and for deriving probability distributions based on spread between assessment made by multiple experts.	Engineering judgment is used extensively in assessing component degradations, degrees of simultaneity (overlapping) and shared causes based on event descriptions (even if basics are included in ICDE-data).	Extensively used throughout the process. Recommended and used in pilot applications to assess robustness of scenario definitions (basic assessment + redundant assessment).
Quantification method	Modified Binomial failure rate model (CCF shock model)	Impact vectors are used as plant-specific input to an empirical Bayes process to get plant-specific CCF-rates and probabilities.	Not specified, the resulting net impact vectors can be used with any method.
Consideration of test staggering etc.	Staggering is considered in a conservative way. (Two consecutive tests have to occur, before it is assumed, that a CCF is noticed and repaired)	Staggering considered in transformation of CCF rates to probabilities of CCF events.	Test staggering is considered by the possibility of special treatment, applied as treatment of time-spread-events
Source plants / source CCG:s.	Wide definition. Possibility for use of applicability factor in case operating conditions for CCG:s differ considerably.	Preferably same CCG-size systems, same component types. Priority plants in ICDE-system.	Wide definition ("all Nordic CCG:s of same size"). Based on component type, without consideration of differing operating conditions for CCG:s.
"Unique" characteristics (not found in other two methods)	<ul style="list-style-type: none"> Assumption of binomial distribution of number of components failed per event "Formula driven" mapping up (BFR) Use of application factor Use of widening factor C to expand resulting distribution. 	<ul style="list-style-type: none"> Plant-specificity by Bayesian methodology Yields uncertainties naturally Event- and formula driven impact vectors Impact vector formalism Plant-specificity 	<ul style="list-style-type: none"> Event-driven impact vectors Impact vector formalism
Specific features with potentially high impact on CCF data/parameters.	<ul style="list-style-type: none"> Coupling parameter and BFR model results in high probability of CCF with higher multiplicities. Application factor Expert judgement 	<ul style="list-style-type: none"> No pre assumptions on the ratios between different failure multiplicities Assumption of complete dependence 	<ul style="list-style-type: none"> Scenario definition Instable in case of few data Difficulty of estimating uncertainty Expert judgment

Characteristic	PEAK / Germany	Fortum / Finland	NAFCS / Sweden
		between degradation values in case the event information does not show else • Expert judgement	

Table 5. Overview of the methods.

6 Benchmark Application

A benchmark exercise was arranged with the purpose to estimate CCF rates for centrifugal pumps and emergency diesel generators using three different approaches; Swedish, Fortum Nuclear Services and GRS methodology. Three data sets were used in this benchmark:

- by using only Nordic data
- by using only German data
- by lumping together all data

No distinction was made between running failures and failures to start. This approach has been used in the actual Nordic methodologies though. Applications have been made, first based on own interpretations of event and observations and then based on a harmonized data set.

6.1 Benchmark 1

All events have been considered with no distinction of failure mode.

Conservative boundary conditions have been used every where.

The Finnish results take into account only the plants with 4-redundant components, whereas the German results take into account all redundancies. E.g. DE-13 has 2, DE-20 has 6, DE-5 has 2 and DE-9 has 3 emergency diesels. Therefore Finnish results have only 16 plant-specific values for diesels.

The different interpretations made of the events resulted in deviations concerning which events that were taken into account in the quantifications. An important observation is how interpretation of which system to account for should be made. This became clear in a discussion of whether or not to account service systems when considering centrifugal pump data. Consideration of detection mode for events is another aspect that was treated differently. The different interpretations on which data to consider has shown to be the main reason for deviations, and naturally this is an aspect with impact on the results.

6.2 Benchmark 2

In the applications based on own interpretations the main differences in the results originated from varying data set. In the application based on a harmonized data set, the main differences could be expected to be eliminated. Deviations could still be observed though, indicating differences in the methods. Some differences could still be caused by different interpretations of events, but it is more likely to be an affect of particular features of the methods that influence the results in different ways and to various extents. Different interpretations and use of model parameters, such as time factor, shared cause factor, applicability factor and impairment vector considerations are some aspects that leads to differences between the CCF estimates. An example of this is that in the Fortum methodology more component groups are defined for which distinct CCF rates are estimated using only relevant event data (not an applicability factor). Further details on different characteristics of the methods were provided in chapter 5 and will be discussed in chapter 7. A comparison of results is given in the following diagrams for Diesel generators and for pumps respectively.

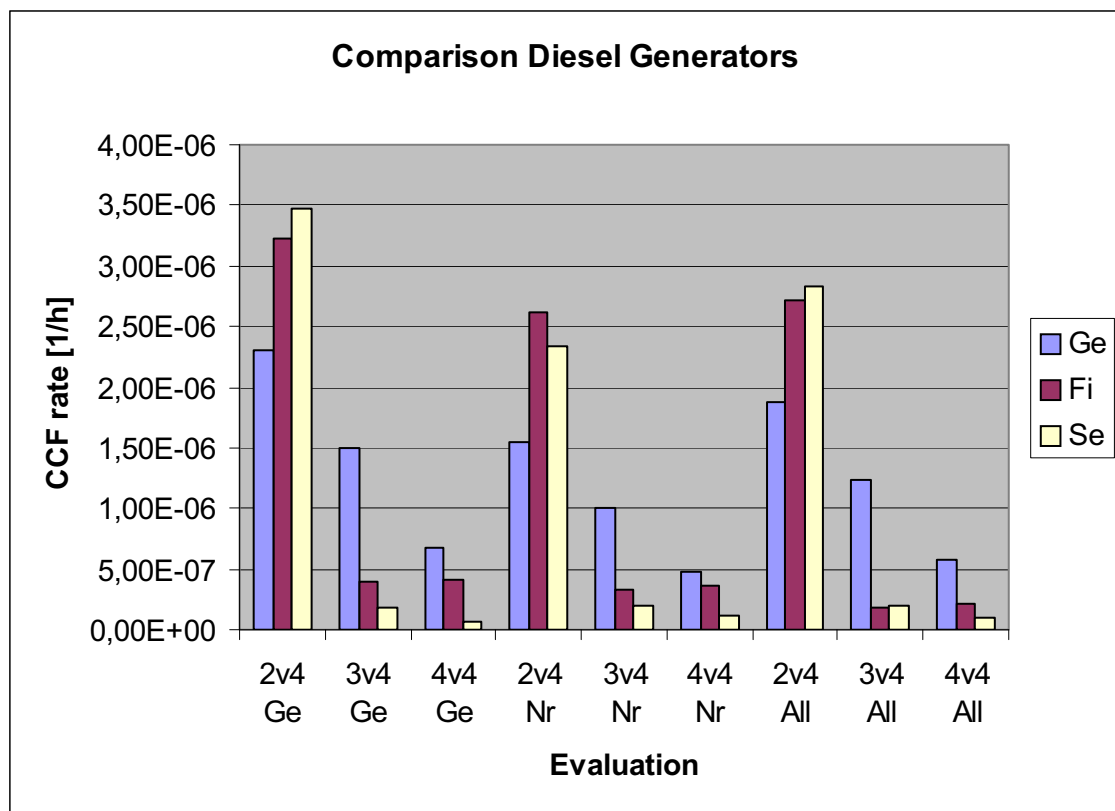


Figure 3. Comparison of CCF rate estimations on diesel generators.

In figure 3 it can be seen that the NAFCS-rates decrease steadily for increased failure multiplicity. It can also be noted that the Fortum evaluation provides rates for 4/4-failures that is higher than for 3/4-failures. In general it seems that results from analysis of diesel data depends only slightly on data source.

In case of Diesel generators, it can be seen, that there is a tendency for the German PEAK method to produce comparatively large values for higher redundancies, and comparatively small ones for lower redundancies. This is what has been expected from

practical experience. The experience or data in this benchmark shows that the numbers of "All" failures are the following, depending on the interpretation:

- 4...9 2/4-failures,
- 0,2...0,6 3/4-failures and
- 0,2...0,6 4/4-failures.

Thus, in view of the data the rates of 2/4-failures should be an order of magnitude higher than the rates of 3/4- and 4/4-failures.

In case of pumps, this tendency is not quite as clear. As can be seen from the next diagram, this is still true for the Swedish evaluation, but not for the Finnish one. This is due to a lack of data, which causes the Swedish approach to work only for the combined data source. The something close to a zero failure statistics explains the surprising Finnish result, that the results for the combined data will not lie between the single sources, but are the smallest. This same effect is also seen with the diesel results for 3/4- and 4/4-failures. The number of failures stays the same when you add observation time. Thus, the numerator stays the same whereas the denominator increases - the complete set must give smaller values.

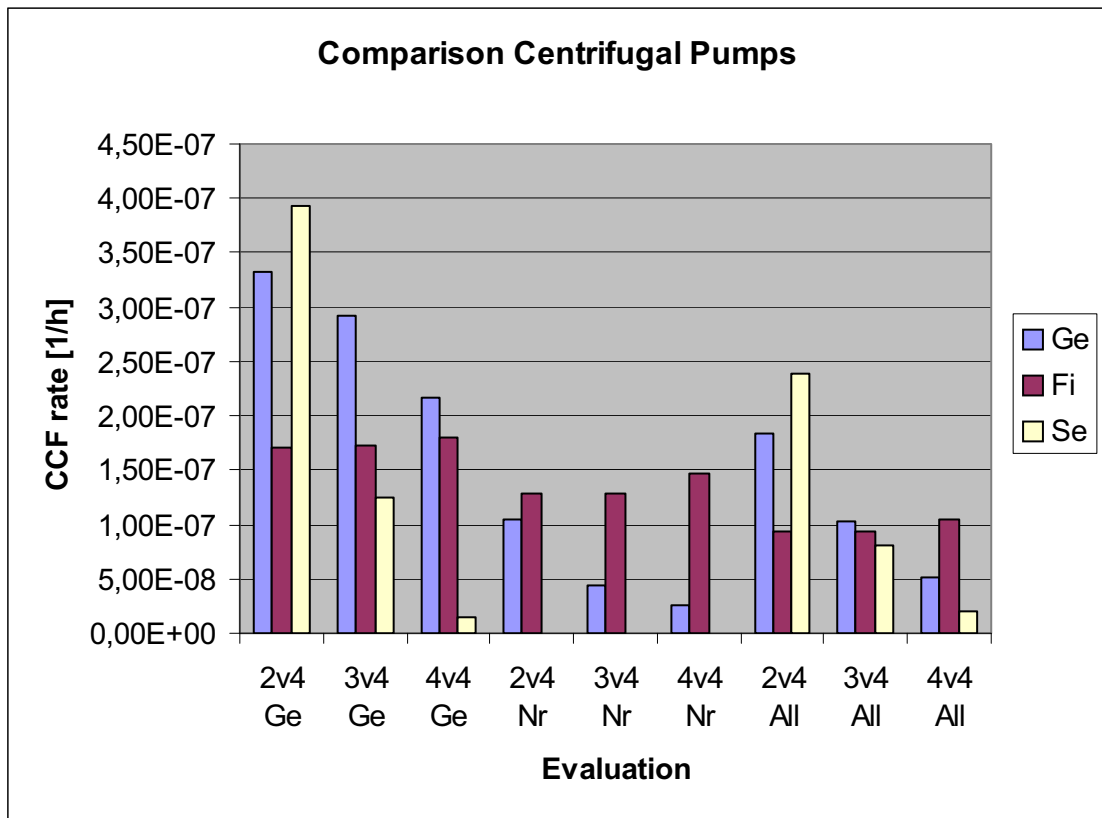


Figure 4. Comparison of CCF rate estimations on centrifugal pumps.

Finnish results for pumps are even more constant than the German ones. The results show the same tendency as observed before for the Diesels. It is the data interpretation which plays role here. The Finnish results are according to the data (as it was interpreted) which say that the number of 4/4-failures is higher than 2/4- or 3/4-failures (all of them between 0,3...0,4 according to the Finnish way to construct impact vectors).

The number of 2/4-failures is equal to the number of 3/4-failures. A general note to be made here is that evaluations of Nordic events lead to much lower rates.

6.3 Discussion

The performed benchmark application has shown that how the data is interpreted is of significant importance. Methodological differences can more easily be evaluated, since there are established approaches that can be compared, while the issue of data interpretation is more about a harmonization on the view of CCF and can not that easily be compared.

7 Conclusions

7.1 Comparison of resulting CCF-rates

CCF rates look rather similar at first sight. However, the following has been observed:

- If there are many events (like in the Diesel example) there is a clear tendency for the German data, that large multiplicities (4/4) become larger than the Nordic results, whereas for small multiplicities (2/4), the opposite holds.
- In case of few events (like in the pumps example), German PEAK results, as well as Finnish results show a tendency to produce similar values for each number of multiplicities. Only the Swedish results indicate small results for large number of multiplicities and v.v.
- This could be interpreted in such a way, that a behaviour, which can be justified by lack of data in case of the Finnish method, remains persistent in case of the German PEAK method for all cases.

So, what has been observed can be theoretically explained, and most has been expected. It is beneficial to have more events by enlargement of the populations under consideration. Speed of convergence differs; in case of PEAK, it is apparently zero.

7.2 Comparison of Methods

In this benchmark the estimation methods were not properly compared because the development of impact vectors played such an important role. Some clear differences are

- the coupling factor of PEAK method (German) tends to limit degree of freedom to quantifying different CCF-multiplicities and forces quantitative values away from empirically more justified values
- if there are no observations or clearly less than 1, e.g. 0.1...0.3, the PREB method (Fortum) yields results that are similar for different CCF-multiplicities.

7.3 Conclusions for Harmonization

- I. Good features were found in all approaches. We should try to take them and develop the existing approaches into a harmonised direction.
- II. The usefulness of the plant-specific posterior estimates needs to be considered.
- III. Impact vectors are useful and expert judgement is often needed to estimate them. A proper expert judgement needs often good knowledge of the plant, system, component and event. This knowledge cannot be found from the ICDE database. All of the methods use engineering judgment, by necessity.
- IV. The applicability factor could be used for the plants in the data source and for the events, in order to properly take into account the effect on the observation times.
- V. The degradation value 0.01 is sometimes useful and could be considered for the data of other countries as well, not only Germany.
- VI. Interpretations of latent and monitored failures have large effect on the results of final CCF unavailability estimation. If monitored failures are considered to be possible all the time, then their effect on the final unavailability value is usually negligible because of the very short unavailability time. We have such an example in the data. If we have monitored failures that are considered to develop only during running time (of a normally standby pump or diesel generator), then their rate is really high because of the typically short running times that are the observation times in this case. This could be one reason to distinguish the failure modes “failure to start” and “failure to run”.
- VII. Concerning the uncertainty estimation, notice that the empirical Bayes approach and the idea of equivalent observations, as in the Fortum method, yields naturally uncertainty distributions for final posterior estimates that include both the statistical and subjective uncertainties.
- VIII. Harmonization of the use of time factor and shared cause factor by NPSAG (according to ICDE) and the application factor by VGB/GRS would be rewarding.
- IX. A next step could be to develop and agree on event & formula driven impact vector creation based on component impairments, time differences and shared cause assessment.
- X. When we have too few events results tend to be strange. In this study the numbers of observations of clean water pumps turned out to be too small. Therefore the database needs to be extended. A development of subjective priors was also suggested.
- XI. Similar design features of German and Nordic plants, with participation in ICDE, leads naturally to seeking opportunity to use harmonized approaches in CCF models and/or quantification. The proportion of the 4 train DG systems observations in ICDE is large; Finland, Germany and Sweden part cover 330 group years of group year observations. This represents approximately 60% of the total observation time, in addition UK contribute with 120 years and US with 75 years.
- XII. This situation is similar also for many other components and the conclusion is that 4 train data shall be developed based on an assessment involving the countries with the main contribution to this experience, i.e. take the ownership of the problem. Note that in most PSAs for NPPs with 4-train-

safety-systems 3of4 and esp. 4of 4 CCFs comprise the main contribution to CDF.

- XIII. Findings of this project will be given to ICDE to include qualified information that we consider to be important for quantification purposes.
- XIV. FORTUM- and PEAK-method use the event evaluation already done in the ICDE or together with the GRS, especially the degradation vectors. After that they are more or less formula-driven. The NAFCS-method however needs a second big step of expert judgement in order to get the impact vectors. That means more work to be done and especially a further field for discussions during the independent PSA-review. This would make a justified formula-driven approach attractive for a common method.

7.4 Phase 2

Following the conclusions it was decided to proceed with a second phase of the project. Objectives for phase 2 were formulated as follows based on the results from phase 1 and the discussion during the phase 1 closing seminar.

- Establish a common procedure and model of quantification for CCF events.
- Establish format to allow data to be shared for quantifications and provide interpretation of raw data for exchange and use in quantification models. (This will improve consistency in international in-depth assessment of CCF events for parameter estimation.)
- Provide a common basis for methods and guidelines for data classification and assessment. A common procedure may be more justifiable and more defensible.

The main activities in phase 2 of the project will be the development of harmonized applications. The work will be organized with use of work group meetings and contributions to meetings with assessments and applications as the application develops.

Transfer and exchange of know-how and experience will be an inherent part of the work. The team members will provide inputs to a common data assessment. Components for assessment will be a matter for discussion and agreement in the group.

To reach these objectives and to improve consistency in event assessment and parameter assessment project task will be carried out as follows

- Work on impact vector construction, develop and agree formula driven approach. Development of formula driven impact vector construction using various approaches. Selecting a suitable approach taking into account existing cases for diesels and pumps.
- Work on parameter estimation, test and develop unified method.
 1. Application of separate methods using identical impact vectors to check convergence of results.
 2. Decision on unified approach based on criteria like being defensible, realistic results avoiding conservativeness, etc.

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9 Appendix 1

Enclosures proprietary under the ICDE agreement, 350 pages

Data evaluation guidelines and surveys

1. ES konsult: Survey of Swedish CCF Methodology. 2006018_001 1.0
2. ES konsult: Data Survey. 2006018_002 1.0
3. Fortum: Fortum CCF Methodology
4. RISA123-07_Survey_German_Database
5. RISA124-07_Survey_PEAK_CCF_method

Data test evaluation applications

6. ES konsult: Evaluation of German diesel data. 2006018_003 1.0
7. ES konsult: Evaluation of German pump data. 2006018_004 1.0
8. ES konsult: Assessment results for Nordic and German CCF data. 2006018_005 1.0
9. Fortum: CCF Benchmark.
10. Fortum: CCF2006-L-Diesel_VN.doc
11. Fortum: CCF2006-L-Pump_VN1.doc
12. RISA125-07_German_Benchmark_Results
13. ES konsult: Harmonized data set for emergency diesel generators and centrifugal pumps. 2006018_007 1.0

Documents on comparisons of approaches

14. Vaurio: PROSOL-7001_JKV-ESKonsult-NPSAG_Rev1.doc
15. Vaurio: PROSOL-7002_JKV-ESKonsult-NPSAG-Review_German_Meth_Final.doc
16. ES konsult: Thesis report. 2006018_006 1.0
17. RISA GB: Note on convergence of PEAK
18. Impact Vector example Note JKV 2007-04-13

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