A State of the Practice Investigation Guiding the Development of Visualizations for Minimal Cut Set Analysis

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Abstract: Minimal Cut Set (MCS) analysis is used for the qualitative and quantitative safety and reliability analysis of systems. While many studies concerning MCS computation in the safety domain are found, no study gives a complete and detailed description of the tasks performed by practitioners during MCS analysis. The goals of this study are (1) to elicit the context (including the tasks) of MCS analysis; (2) to obtain the requirements and needs of the safety analysts, and the tools used; (3) and to assess the quality of the tools from the point of view of the safety engineers regarding their (3a) representation, (3b) interaction, (3c) performance, and (3d) usability. We found that the main purpose is finding improvements to increase the hazard's safety. The main tasks are identifying critical basic events, the related system components, and single points of failure. The stakeholders are mainly decision makers and system engineers. The main requirements are finding single points of failure, determining MCS order, and finding basic events with high failure probability and related components. The results show that the usability of the tools is accepted but their information presentation can be improved by providing overviews and the missing interactions.

Keywords: Safety Visualization, user study, minimal cut set analysis, minimal cut set visualization, state of the practice.

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1 INTRODUCTION

Safety is a very important property of embedded systems. Safety analyses are performed to avoid human injury or a negative impact on the environment during system usage. Fault Tree Analysis is a well-known, commonly used method for the safety analysis of embedded systems. In addition to examining the safety of embedded systems, fault tree analysis is also used in reliability and availability analysis [31, 25, 19], among others.

Minimal Cut Set (MCS) analysis is used in fault tree analysis for identifying combinations of so called basic events (BE) that cause a safety problem [6]: p. 9, 58, 188-189, [11, 13, 31]. Here, basic events (BE) are the root causes of a problem. The MCSs help to "identify failure events whose exclusion secures the system" [27]. Excluding these events will considerably reduce the probability of the top level hazard. Additionally, MCSs help in computing the failure probability (FP) of the hazard (if the failure probabilities of the basic events are provided).

Most studies about MCS analysis define MCSs, illustrate their structure, and investigate their computation, such as [42, 39, 38, 12, 20, 40, 41]. However, most studies only refer to a limited number of tasks that are involved in MCSs analysis. For example, Papadopoulos et al. [21] consider only two MCS analysis tasks regarding single points of failure (SPoF), and areas of the design that contributed to the overall failure probability (i.e., BEs), which guides improvement strategies of the system. Patterson et al. [22]: p. 18 consider the susceptibility (i.e., FP) of MCSs for ranking them. This prioritization will help the decision makers in their judgments.

Cepin [7] identified three MCS analysis tasks. Listing MCSs, finding high values of probabilities, and finding a large number of failure events (BEs) are considered important MCS analysis tasks for evaluating a fault tree. However, no studies were found giving a complete detailed task description or describing which information is necessary for MCS analysis from the point of view of the users of tools.

The IBM & Industry Studies, Costumer Interviews [16]: p. 8 reports that 30% of the users' time is spent on searching for and exploring relevant information. Textbooks like the one by Ward et al. [33] show, that interactive data visualization can be used to improve the exploration and understanding of large amounts of data. This is due to the inherently parallel process of perceiving the environment. This process is used by visualizations to convey a large amount of information to the user. It is supported by effective interactions that allow switching between overview and detail, as well as selecting, marking, sorting, filtering, and other mechanisms. Eward Tufte showed not only how to construct effective visualizations [29], but also how visualizations can help to analyze data [28]. Thus, visualizations together with matching interactions allow to deal with huge data sets and allow to analyze them effectively and efficiently.

"Safety Visualization" is a new, emerging domain in visualization meeting the challenges of providing visualizations and advanced interactions for supporting the safety analysis of (embedded) systems. In this domain, innovative visualizations and interaction mechanisms were developed to ease the safety analysts tasks by Al-Zokari et al. [2, 3, 5, 4], Khan et al. [18], and Yang et al. [37, 35, 36]. These visualizations support the practitioners in MCS analysis for assessing the safety, reliability, or availability of (embedded) systems and for suggesting improvements as well as comparing different improvement alternatives or different states of the system. Similarly, Høiset et al. [14] used virtual reality to reveal the consequence of hazards and ease the communication between analysts and stakeholders.

To guide the development and the improvement of visualizations for MCS analysis, this user study was performed. The goals of this study are: (1) to give an overview over the current state of the practice in MCS analysis, (2) to support sharing the experience of safety analysts with the visualization domain in the near future, and (3) to understand the requirements of the users of safety tools, aiming at understanding the world as experienced by the safety analysts.

2 RESEARCH PURPOSE AND RESEARCH QUESTIONS

This research aims at exploring the state of the practice regarding MCS analysis from the perspective of practitioners, i.e., safety engineers. The results of this research are intended to provide guidelines for enhancing the visualizations and the interaction capabilities of current tools supporting MCS analysis and for developing new visualizations and new tools that support MCS analysis. In particular, it focuses on the following research questions:

RQ-1 In which context do safety engineers perform MCS analysis?

RQ-2 What are the requirements of the safety engineers for performing MCS analysis?

RQ-3 How is the quality of current tools for performing MCS analysis perceived by the safety engineers?

Here, quality means to which extent the visualization and the interaction capabilities provided by the tools for performing MCS analysis support the safety engineers while performing MCS analysis. We decompose the quality of tools for performing MCS analysis as follows:

RQ-3a What is the practitioners' perception of the quality of information representation? The degree to which the representation of the information provided by a tool for performing MCS analysis is adequate, understandable, and necessary for performing MCS analysis. A good representation of the information generated by MCS analysis should help reducing the time and the effort required to perform the analysis tasks while reducing errors by, e.g., giving a good overview.

RQ-3b What is the practitioners' perception of the quality of interaction capabilities? The degree to which the interaction capabilities provided by a tool facilitate the MCS analysis, such as navigating through views, sorting data, and filtering data.

RQ-3c What is the practitioners' perception of the usability? Usefulness: The degree to which a safety engineer believes that using the tool for performing MCS analysis will help him or her to attain gains in job performance [32]: p. 447. Ease of use: The degree of ease associated with the use of the tool for performing MCS analysis [32]: p. 450. Usability: The tools' clarity, understandability, becoming skillful with, easiness, and the ability to learn their functionality. Usability comprises both usefulness and ease of use.

RQ-3d What is the practitioners' level of satisfaction with current tools for performing MCS analysis?

Comparing the capabilities of the current tools performing MCS analysis and the requirements of the safety analysts enables to identify the strengths and the drawbacks of these tools and then to suggest improvements for supporting the tasks of the analysts. Finally, the practitioners were asked whether they prefer 2D or 3D interactions when analyzing MCSs.

3 RESEARCH METHODOLOGY

3.1 Survey Design

We designed an online survey in order to reach a large sample of safety engineers. The related questionnaire was designed according the guidelines given in [9, 10, 23] and can be accessed using this link [1]. The final version included up to 33 questions (34 for the second survey). The questionnaire comprised open, dichotomous, polychotomous, and multiple choice questions. All opinion questions included the alternative answer "I do not know". Filters were used to avoid overwhelming respondents with unnecessary questions and to ensure that they answered based on firsthand experience. Furthermore, definitions and examples were added to avoid misinterpretation of the questions.

To elicit the context in which safety engineers perform MCS analysis (**RQ-1**), 10 questions were designed comprising questions regarding target purposes, tasks, stakeholders and information exchange with them, hazard sizes (time), effort, and tools for performing MCS analysis they have used.

Seven questions were prepared for gathering the requirements (**RQ-2**) regarding the identification, analysis, and comparison of basic events and minimal cut sets. Moreover, respondents were asked about the importance of the required information. We identified possible needs of information based on a literature review and in collaboration with a safety expert.

Another 13 questions were designed for collecting information about the quality of current tools for performing MCS analysis (**RQ-3**). These questions were asked only to safety engineers with experience in using at least one tool for performing MCS analysis. Four questions were designed for eliciting the quality of the information representation by focusing on its understandability, appropriateness, and support for getting relevant information in one sight (**RQ-3a**). For analyzing completeness, we compared the importance of required information with the information provided by current tools. Three questions aimed at eliciting the quality of interaction capabilities, i.e., navigating, filtering, and sorting (**RQ-3b**). Two questions measured the usability according to the TAM model [32] (**RQ-3c**). Another three questions were specified to elicit the satisfaction level of safety engineers regarding current tools for performing MCS analysis (**RQ-3d**). There was one additional question whether the participants prefer 2D or 3D interactions.

Finally, five demographic questions (marked 'DQ') were prepared for eliciting the respondents' age, position, working experience, and experience and frequency in performing MCS analysis. They allow to assess if the sample matches the target group of experienced MCS analysts.

3.2 Population and Sampling Strategy

Practitioners and safety experts were invited to participate in an online user study that elicits their purposes, their requirements, and their tasks, as well as their experience with tools regarding visual representation, interaction, and usability. The target population includes safety engineers with experience in MCS analysis and in using tools for MCS analysis. We first drew a purposive sample consisting of 29 safety experts who were identified using Google search and personal email contacts. This sample comprised researchers and practitioners. We included researchers who closely worked with practitioners in the context of MCS analysis or use tools for performing MCS analysis. As an additional sample, we invited 11 safety experts contacted during the conference PSAM11&ESREL 2012. In both cases, all participants were encouraged to invite other safety experts to the survey (snowball technique).

3.3 Implementation and Pre-Evaluation

The survey was implemented using the on-line, free, open source tool LimeSurvey [8]. The data was retrieved using an export facility of this tool. After implementing the survey in LimeSurvey, we performed a pre-evaluation to appraise its completeness, understandability, and consistency [10]. In particular, one expert in experimental design and one expert in visualization reviewed the survey. All questions were classified as necessary, but the reviewers considered the survey being too long and some questions being too complex. Thus, we simplified the questions' wording, restructured the survey into seven sections to reduce its complexity, and added filters for not overwhelming respondents with unnecessary questions. Furthermore, we added the fields "Other" and "None", and fields for comments to make the survey more flexible. The answers were randomized.

3.4 Execution

The survey was performed twice. On February 17, 2012, we sent 29 invitations to experts working in safety analysis and developing safety analysis tools. The deadline for participation was March 9, 2012. On June 25, 2012, we sent 11 additional invitations to the safety experts contacted during the conference PSAM11&ESREL 2012. The deadline for these participants was July 5, 2012. An additional participant was invited on December 18, 2012. In all cases, the invitation subsumed the research purpose and scientific value, the target sample, the confidentiality and the anonymity of responses, the expiry date, and the contact person. Anonymity was guaranteed through the use of tokens. Aiming at increasing the response rate, a reminder email was sent one week after the original invitation.

3.5 Data Analysis

The data analysis reported in the subsequent sections was performed using SPSS Statistics 17 [15]. Because several questions were asked to a specific group of respondents or were optional, we explicitly report the total number of subjects (N) who answered a question and the frequency an option is selected (n). For each research question, the question types used and the related questions are listed in Table 1. For each question type, the response scale and the reported statistics are listed in Table 2. In particular, we report descriptive statistics including the sample median (Mdn), p, Z, and frequencies.

Table 1: Research Question, Question Type, and Related Questions. (Note: The question q6-1 did not exist in the on-line survey).

Research Question	Question Type	Questions
Demographics (DQ) 4.1	Polychotomous	q1-1, q1-2, q7-1, q7-3
	Multiple choice	q7-2
RQ-1 4.2	Polychotomous	q1-4
	Selection	q2-3
	Multiple choice	q1-3, q1-5, q1-6 q2-1, q2-2
	Quote	q1-7S1, q1-7S2, q1-8S1, q1-8S2
RQ-2 4.3	Polychotomous	q3-2a, q5-8, q6-2, q6-3, q6-5, q6-6
	Dichotomous	q3-2b, q5-3
	Quote	q5-4, q6-4
RQ-3 4.4	Polychotomous	q3-1, q3-4, q4-3, q5-1, q5-2, q5-5, q5-6, q5-7
	Dichotomous	q4-1, q4-2
	Multiple choice	q3-3, q3-5

Table 2: Question Type, Response Scale, and Statistics Reported.

Question Type	Response Scale	Statistics
Dichotomous	Yes, No	N, #Yes, #No
	Complete, Incomplete	N, #Complete, #Incomplete
	2D, 3D	N, #2D, #3D
Selection	Nominal	n
Multiple choice	Nominal	n
Polychotomous	5-point Likert scale	n, Mdn, p, Z
Open	Quotes	Quotes

Taking into account the sample size (17) and that variables are not normally distributed (normal distribution was tested using the Shapiro-Wilk test and analyzing the histograms), we analyzed the difference of the tendencies using the Sign two-tailed significance test with a default value of $\alpha = 0.05$ (95% confidence level). For the five-point Likert scale data, we were interested in which items produced a meaningful opinion from the respondents, i.e., a response significantly different from a test-value, e.g., H0: $Mdn(x) =$ test-value and H1: $Mdn(x) \neq$ test-value. If not mentioned, the test-value is the midpoint (i.e., neutral = 3), according to the guidelines defined by Utts and Heckard [30]: p. 610. For these tests, we report the significance level (p) and the Sign test observed value (Z). If the p- or the Z-value are significant, then they are printed in **bold**. If no significant difference is found, the tendency of the answers is reported. This tendency is the comparison to the central tendency Mdn of the 5-point Likert scale (i.e., value 3) since the data is ordinal as recommended by Russell [24]: p. 118, Szafran [26]: p. 97, and Wohlin et al. [34]: p. 124. The final data set and the survey are stored in the repository available from [1].

4 RESULTS

Out of 40 invitations sent, 18 safety experts answered the survey. This is a response rate of 45%. The responses of one participant were eliminated because he or she did not complete the survey. Thus, we have a sample size of 17. The average time for completing the survey was 26 minutes (SD = 17). 16 participants were invited using the purposive technique and one additional participant was invited through the snowball technique.

4.1 DQ: Demographic Questions and Experience in MCS Analysis

Out of 17 participants, six were working in Industry, six at the University, three at a research institute, one was working in both industry and at a research institute, and one was working in both industry and at the university. The participants are assumed to be experienced if they have at least 3 years of working experience, and are performing MCS analysis at least for 3 years and at least sometimes. 82% of the participants ($n = 14$) have at least 3 years working experience. 64.7% ($n = 11$) of the participants have at least 3 years of experience in performing MCS analysis (i.e., 6 participants have more than 6 years and 5 have from 3 to 6 years). Finally, one participant performs MCS analysis always, three very often, eight sometimes, and five rarely. Overall, the results show that they are experienced in work and experienced in MCS analysis with statistical significant difference: work experience ($Mdn = 5$: "More than 6 years", $p <$**0.001**, $Z = 3.47$, test-value = 2: "1-2 years"), MCS analysis experience duration ($Mdn = 3$: "3-4 years", $p = 0.057$, $Z = 2.94$, test-value = 2: "1-2 years"), and MCS analysis frequency ($Mdn = 3$: "Sometimes", $p <$**0.001**, $Z = 3.17$, test-value = 4: "Rarely").

4.2 RQ-1: Context of Performing MCS Analysis

4.2.1 Practitioners' Main Purposes and Main Tasks While Performing MCS Analysis

Purposes of using minimal cut set analysis**:** Out of 17 participants, 11 use MCS analysis to "Find improvements to increase the hazard's safety", 5 use it to "determine the safety level of the hazard being analyzed", 5 to "compare alternative improvements to increase the hazards safety", and 5 to "analyze the hazards safety evolution after system changes". Seven respondents added open comments stating that they have also used MCS analysis for: fault diagnosis (frequency = 1), verifying model consistency (1), reviewing a fault tree (1), identifying single points of failures (SPoF) (1), customer request (1), determining accurate representation of the accident sequence and identifying dependencies (1), and reliability analysis (1).

MCS analysis tasks**:** According to the participants ($N = 17$), the tasks performed *always or very often* are: identifying the most critical BEs ($Mdn = 2$, $p <$ **0.001**, $Z = 3.474$); identifying system components related to BEs (2, **0.002**, 2.94); identifying SPoF (1, **0.007**, 2.582); and calculating the failure probability (FP) of a hazard (2, 0.804, 0.25). Tasks that are performed *sometimes* include: calculating the failure probability (FP) of all MCSs (3, 0.388, 0.866); calculating the FP of some MCSs (3, 0.549, 0.6); identifying the number of MCSs causing a hazard (3, 0.774, 0.289); classifying MCSs regarding their order (3, 0.774, 0.289); and identifying all BEs of the hazard (3, 1.000, 0). Finally, only one MCS analysis task is performed *rarely*: classifying MCSs regarding their FP (4, 0.267, 1.1).

4.2.2 Stakeholders of the Practitioners and Required Information

Stakeholders: The participants working in industry ($N = 8$) provide the information gained from their MCS analysis to decision makers ($n = 4$), customers (4), system engineers (4), safety engineers (3), and software engineers (2). Additionally, the participants working at a *university* ($N = 7$) report to safety engineers ($n = 5$), system engineers (4), decision makers (2), and software engineers (1). Finally, the participants working at a *research institute* ($N = 4$) report to safety engineers ($n = 3$), customers (3), software engineers (2), decision makers (2), and system engineers (2).

Required information: Stakeholders ask the participants ($N = 17$) for: a list of prioritized possible causes of a hazard (i.e., a list of prioritized MCSs) ($n = 12$), a list of SPoF that may cause a hazard (11), the combination of failures that may cause a hazard (i.e., MCSs) (10), a list of failures (i.e., BEs) with larger impact on hazard's safety (8), and suggestions for increasing the hazard's safety (7). Approximately one third of the respondents provide the hazards' safety evolution after system improvements (5). Less than a third provide: the safety level of the hazard being analyzed (4), the generated information from MCS analysis (4), and the properties of the system components related to the failures (3).

4.2.3 Hazard sizes and Time Spent for MCS Analysis

Hazard size: Up to six participants ($N = 9$) of the first survey defined a hazard size in terms of its number of BEs and its number of MCSs (Table 3). At the time of the second survey, the participants ($N = 8$) have analyzed hazards of size 1-30, 1-100, 1-100, 1-400, 1-500, 1-1,000, 1,000-10,000, 10,000-100,000 MCSs.

Table 3: Hazard Size. "Format": number given (number of times mentioned).

Hazard size	Number of BEs	Number of MCSs
Small	1-3, 10 (3), 20	3, 10 (3)
Medium	4-20, 50, 100 (3), 100-1,000	25, 30, 100 (2)
Large	≥20, 100 or more, 1,000 (2), ≥1,000, 10,000	50 or more, 1,000 (2), 3,000

Time spent on comparing two hazards of an average (medium) size regarding their SPoF: All participants ($N = 8$) of the second survey answered this question (Table 4).

Table 4: Time Spent for Comparing Two Hazards Regarding SPoF.

Hazard Size	Range	Average Hazard Size	Time for Performing Comparison
Small	1-30 MCSs	15 MCSs	5 minutes
	1-100 MCSs	50 MCSs	10 minutes, 2 days
Medium	1-400 MCSs	200 MCSs	0 minutes
	1-500 MCSs	250 MCSs	2 hours
	1-1,000 MCSs	500 MCSs	2-10
Large	1,000-10,000 MCSs	5,000 MCSs	2-4 hours
	10,000-100,000 MCSs	50,000 MCSs	2-10

Time spent in performing MCS analysis tasks: Up to six of the participants ($N = 9$) from the first survey answered this question. The estimation time for analyzing: *small* hazards are: 2 minutes using FaultTree+ (3 MCSs), 2 hours using C^2FT (10 MCSs), a range of minutes using self-developed tool (10 MCSs), and 1 day using ESSaRel (10 MCSs). The time spent for analyzing *medium* hazards are: 30 to 60 minutes using MagicDraw, a range from minutes to hours using self-developed tool (100 MCS), and a range from 2 to 3 days using FaultTree+ (30 MCSs); and for analyzing large hazards it takes from minutes to hours using self-developed tool (1000 MCSs), and from 2 to 3 days using FaultTree+ (3000 MCSs). The remaining answers were stated as "depends".

4.2.4 Tools Used for Performing Minimal Cut Set Analysis

Tools used: For performing MCS analysis, respondents working in *industry* ($N = 8$) have used RiskSpectrum ($n = 3$), CAFTA (1), FaultTree+ (1), ESSaRel (1), CARA (1), BlockSim (1), C^2FT (1), self-developed tools (1), and WinNUPRA (1). At *universities* ($N = 7$) respondents have used ESSaRel ($n = 4$), BlockSim (3), FaultTree+ (2), RAM Commander (1), self-developed tools (1), Item toolkit (1), RiskSpectrum (1), and WinNUPRA (1). At *research institutes* ($N = 4$) they used ESSaRel ($n = 4$), FaultTree+ (3), C^2FT (1), and MagicDraw (1). Thus, the most used tools are ESSaRel (8), FaultTree+ (5), BlockSim (4), and RiskSpectrum (3).

Best tools: Respondents working in *industry* consider the best tools for performing MCS analysis to be CAFTA (2), RiskSpectrum (2), Fault Tree+ (1), BlockSim (1), SAPHIRE (1), C^2FT (1), and WinNUPRA (1). The participants from *universities* consider that the best tools are ESSaRel (3), BlockSim (2), CAFTA (1), and RAM Commander (1). The participants from *research institutes* reported the best tools being Fault Tree+ (3), ESSaRel (1), C^2FT (1). Therefore, the best tools for performing MCS analysis of the majority of the participants are ESSaRel (4), BlockSim (3), Fault Tree+ (3), CAFTA (2), and RiskSpectrum (2).

Best tool currently used: Participants working in *industry* ($N = 6$) consider the best tool currently used for performing MCS analysis to be RiskSpectrum ($n = 2$), CARA (1), Blocksim (1), C^2FT (1), and WinNUPRA (1). At *universities* ($N = 7$) they report the best tool to be ESSaRel ($n = 3$), BlockSim (1), RAM Commander (1), RiskSpectrum (1). At *research institutes* ($N = 4$) the best tools are reported to be FaultTree+ ($n = 2$), MagicDraw (1), and C^2FT (1).

The following analysis refers to the best tool that participants were using for performing MCS analysis at the moment of the survey.

4.3 RQ-2: Requirements of the Safety Engineers for Performing MCS Analysis

Necessary information: The most *necessary* information from the point of view of the respondents for performing MCS analysis are shown in the first four rows in Table 5: SPoF, MCSs' order, BEs with high FP, and system components related to BEs. The information that tend to be necessary is shown in the fifth to the tenth row in this table.

Additional information: Out of 15 respondents, 11 do not need additional information for performing MCS analysis. However, the remaining respondents need information regarding: "*Fault Tree structure*", "*The path from hazard to a specific basic event*", "*What are the architectural components providing the largest amount of Basic failures or MCS*", "*Accident sequences*", "*Dependency matrices*", "*System Layouts*", "*Sensitivity and uncertainty analysis*", "*Test data to try to (re)create hazards*", "*Qualification data*", "*Heritage data*", and "*Standards*".

MCS analysis tasks: The first seven tasks in Table 6 are the most important tasks needed to be performed during MCS analysis: finding mistakes in the structure and incomplete information, prioritizing MCSs, showing the system parts related to BEs and their properties, knowing

Table 5: Necessary information during MCS analysis.

No.	Information option	n	Mdn, p, Z
1	SPoF	13	1, **0.003**, 2.774
2	MCSs order	13	1, **0.012**, 2.412
3	BEs with a high FP	14	1, **0.022**, 2.219
4	system components related to BEs	13	1, **0.039**, 2.021
5	FP of BEs	13	1, 0.092, 1.664
6	FP of the MCSs	12	1, 0.334, 0.949
7	BEs with high number of occurrence	14	2, 0.146, 1.443
8	FP of a hazard	12	1.5, 0.227, 1.206
9	MCSs with a high FP	14	1.5, 0.267, 1.109
10	properties of system components	11	2, 0.745, 0.316
11	total number of basic events	13	3, 1.00, 0.00
12	MCSs with identical basic events characteristics	12	3.5, 1.00, 0.00
13	total number of MCSs	14	5, 0.581, 0.555
14	MCSs with identical order	12	4.5, 0.227, 1.200
15	MCSs with identical failure probabilities	12	5, **0.021**, 2.214

Response scale: 5-point Likert scale from 1: necessary to 5: unnecessary.
Results with statistical significance (i.e., $p < 0.05$) are marked in **bold**.

BEs with high number of occurrence, exploring the systems' model and interacting with it, and comparing MCSs regarding their order. All other tasks except the last four in Table 6 tend to be needed for performing MCS analysis from the point of view of the respondents.

One participant did not use any tool at the time of the survey. Therefore, the respondent answered only the questions related to the information of MCS analysis and not related to the tools. This participant considers the following as ***necessary information:*** SPoF, basic events (BEs) with high number of occurrence, BEs with high FP, system components related to BEs, MCSs with high FP, properties of system components, MCSs with identical FPSs, and the total number of BEs. Finally, this participant reported the ***MCSs tasks*** to be: to know the system being analyzed, to know and to present the parts of the system that are related to the BEs in a hazard, and to know if the hazard is safe or not.

4.4 RQ-3: Quality of Current Tools for Performing MCS Analysis as Perceived by the Safety Engineers

4.4.1 RQ-3a: Practitioners' Perception of the Quality of Information Representation

Information representation: The results from performing MCS analysis are represented differently by the tools at the time of the survey. Nine out of 15 respondents report that this information is represented as text (using FaultTree+, ESSaRel, CARA, RiskSpectrum, or BlockSim tools). Additionally, nine report that the information is represented in a tabular form (using FaultTree+, ESSaRel, MagicDraw, RiskSpectrum, WinNUPRA, C^{2}FT, or RAM Commander). Only five stated that the information is represented in fault tree structures (FaultTree+ or ESSaRel). Finally, only two stated that the information is represented using block diagrams (using FaultTree+, ESSaRel, C^{2}FT, or WinNUPRA).

Understandability of information: The respondents find the information provided by the tools to be *understandable* ($n = 15$, $Mdn = 2$, $p = \mathbf{0.012}$, $Z = 2.41$).

Table 6: Degree of necessity of MCS analysis tasks.

No.	When performing MCS analysis I need to:	n	Mdn, p, Z
1	to find mistakes in the hazard structure	11	2, **0.001**, 3.015
2	to prioritize MCSs for detailed analysis	14	2, **0.003**, 2.774
3	to find incomplete information	11	2, **0.004**, 2.667
4	to show the system being analyzed, its physical parts related to basic events, and their properties	13	1, **0.012**, 1.66
5	not to know the BEs with high number of occurrence	8	4, **0.031**, 2.04
6	to explore the system's model and to interact with it	14	2, **0.039**, 2.021
7	to compare between MCSs regarding their order	14	2, **0.039**, 2.021
8	to compare BEs regarding the MCSs' quality (i.e., criticality: e.g., FP, order) that they affect	6	2, 0.063, 1.78
9	do not want to manually calculate the failure probabilities	10	2, 0.070, 1.76
10	to compare between MCSs regarding their failure probability (FP)	14	2, 0.092, 1.664
11	to print and show the physical parts related to basic events (BEs) to the stakeholders	11	2, 0.125, 1.512
12	to know the MCSs that have low order with high FP	8	2, 0.219, 1.22
13	to compare between BEs regarding their number of occurrence	14	2.5, 0.180, 1.333
14	to compare between BEs regarding their FP	14	2, 0.267, 1.109
15	to know the MCSs within a FP range that I specify	9	3, 1, 0
16	to know the MCSs with an order of a range that I specify	7	3, 1, 0
17	not to prioritize MCSs for detailed analysis	7	3, 1, 0
18	not to know the BEs with high FP	8	3.5, 1, 0

Response scale: 5-point Likert scale from 1: strongly agree to 5: strongly disagree.
Results with statistical significance (i.e., $p < 0.05$) are marked in **bold**.

Quality of information representation: The respondents rate the representation of all information as *fair* with respect to: the detail level ($N = 15$, $Mdn = 3$, $p = 0.18$, $Z = 1.33$), the data representation in general (15, 3, 0.125, 1.512), the sequence order in which the information is presented (14, 3, 0.754, 0.316), the arrangement of the information in a single view (15, 3, 0.774, 0.289), and getting an overview in one sight of the hazard (15, 3, 1, 0).

Immediate overview (information in one sight): Nine out of 17 participants state that they can gain an immediate overview regarding: MCSs with the highest FP (using FaultTree+, ESSaRel, CARA, C^{2}FT, MagicDraw, RiskSpectrum, WinNUPRA, or BlockSim), and MCSs with SPoF (using FaultTree+, ESSaRel, MagicDraw, CARA, C^{2}FT, or BlockSim). Six of the participants ($N = 17$) reported that they are able to get an immediate overview regarding: MCSs with low order (using FaultTree+, ESSaRel, MagicDraw, WinNUPRA, C^{2}FT, or BlockSim). Five of the participants ($N = 17$) reported that they get an immediate overview regarding BEs' number of occurrence (using FaultTree+, RiskSpectrum, or BlockSim), and system design (using FaultTree+, ESSaRel, C^{2}FT, RiskSpectrum, or BlockSim). Finally, only four respondents of ($N = 17$) get an immediate overview regarding: Safety level of the hazard being analyzed (using FaultTree+, ESSaRel, WinNUPRA, or BlockSim), and MCSs affected by a BE (using FaultTree+, C^{2}FT, WinNUPRA, or BlockSim).

4.4.2 RQ-3b: Practitioners' Perception of the Quality of Interaction Capabilities

Sorting the information: The participants (N = 17) report that the best tool used at the time of the survey provides the interaction capability of sorting for: MCS's FP (no = 2, yes = 8, provided by FaultTree+, BlockSim, RAM Commander, C^{2}FT, MagicDraw, RiskSpectrum, WinNUPRA) and MCS's order (no = 3, yes = 9, provided by FaultTree+, BlockSim, RAM

Commander, C^2FT, MagicDraw, RiskSpectrum, self-developed). However, most of the tools do not provide sorting regarding: BE's FP (no = 7, yes = 4, only provided by BlockSim, RiskSpectrum, self-developed), both MCS's FP and order (no = 6, yes = 3, only provided by FaultTree+, BlockSim, RiskSpectrum), and BE's number of occurrence (no = 8, yes = 2, only provided by FaultTree+, RiskSpectrum). Furthermore, no tool can provide the sorting of both BE's FP and BE's number of occurrence (no = 9).

Filtering the information: Six out of 10 of the participants stated that the best tool used for performing MCS analysis supports filtering regarding: MCS's order (using FaultTree+, BlockSim, RAM Commander, C^2FT, RiskSpectrum, WinNUPRA). The respondents were half split regarding the filtering options: MCS's FP and the BE's FP. Respondents using BlockSim, RAM Commander, RiskSpectrum, WinNUPRA reported the availability of filtering by MCSs FP. Respondents using BlockSim, RAM Commander, RiskSpectrum, and WinNUPRA report the availability of filtering by BE's FP. Only 2 of the participants state that the best tool can filter by BEs' number of occurrence (using FaultTree+, WinNUPRA).

Interaction amount: The participants report that the amount of interaction needed for getting the complete information in *navigation*, i.e., navigating through views ($n = 10$, $Mdn = 3$, $p = 1$, $Z = 0$) and navigating through the hazards' structure (10, 3, 1, 0) are considered to be *just right*. However, they rated the amount of *scrolling up/down in the same view* to be *too much* (11, 2, **0.031**, 2.04).

4.4.3 RQ-3c: Practitioners' Perception of Usability

Ease of use: The respondents find the best tool they are currently using: easy to learn ($n = 13$, $Mdn = 2$, $p =$ **0.039**, $Z = 2.0$). They tend to find it: clear and understandable (13, 2, 0.065, 1.8), easy to become skillful in using it (12, 4, 0.065, 1.8 negated), and easy to become skillful in MCS analysis when using it (12, 2.5, 0.289, 1.06). However, the participants are unsure, if the tools are easy to use (13, 3, 0.754, 0.316 negated).

Usefulness: The respondents find the best tool they are currently using: useful in their job ($n = 15$, $Mdn = 4$, $p =$ **0.003**, $Z = 2.77$ negated), enables them to accomplish tasks more quickly (15, 2, **0.004**, 3.17), enables them in understanding the system being analyzed (14, 2, **0.022**, 2.2), and increases their productivity (14, 4, **0.039**, 2.02 negated). However, they are unsure, if using the tools enables them to communicate better with the stakeholders (14, 3, 0.125, 1.5).

4.4.4 RQ-3d: Level of Satisfaction with Current Tools for Performing MCS Analysis

Satisfaction level: The respondents are confident that their results are correct because of the information generated by the tool for performing minimal cut set analysis ($n = 15$, $Mdn = 2$, $p <$**0.001**, $Z = 3.175$), would recommend the tools to colleagues ($n = 14$, $Mdn = 2$, $p =$ **0.039**, $Z = 2.02$), and tend to be *satisfied* regarding the best tool they are currently using ($n = 15$, $Mdn = 2$, $p = 0.109$, $Z = 1.58$). The tools used by the respondents that reported their *satisfaction* are: FaultTree+, ESSaRel, CARA, C^2FT, MagicDraw, and RiskSpectrum.

4.5 Do Practitioners Prefer 2D or 3D Interactions When Analyzing MCSs

Five out of seven participants prefer 2D interactions over 3D interactions. Two comments were provided by the respondents to this optional question. One respondent commented: "*In 3D there* *is always the possibility of hiding information in the Z-direction. This bears risks for missing information.*". Another stated: "*In my case it may be relevant to go from the cut-set list to the event tree (or sequences) to understand the failure roots. It is some how more difficult to do in the case of dependencies, but the idea is to help the user to identify the scenario realized through the cutset.*" This question was only asked in the second survey.

5 DISCUSSION OF THE RESULTS

From the results of the demographic section 4.1, we conclude that most of our participants are experienced in MCS analysis, and from different working environments with at least three years of experience. Thus, the sample is representative of the target population. Moreover, most participants were frequently performing MCS analysis tasks (Section 4.1) and all but one were using MCS analysis tools (Section 4.2.4). We conclude that their insights into tools and procedures is up-to-date.

5.1 RQ-1: Context of Performing MCS Analysis

We identified eleven single *purposes* for performing MCS analysis. The participants confirmed all purposes and added additional ones (Section 4.2.1). The use of MCS analysis for several different purposes indicates its usefulness in safety and reliability analysis.

The *purposes and tasks* (Section 4.2.1) identified as frequent in this survey indicate the need of representations for critical BEs, components related to BEs, SPoF, FP of a hazard, etc., to support the analysis. Only the *task* "classifying MCSs regarding their FP" is performed rarely by the participants during MCS analysis. One plausible explanation is that sometimes the FPs of MCSs are not provided to the analysts, because, e.g., the project is still in the design phase or the FPs are not available. FPs might not be available for self-built components, or they are not provided by the component producer.

The *stakeholders* of the participants are mostly safety engineers, system engineers, decision makers, customers, and software engineers (Section 4.2.2).

Furthermore, according to the *information* required by these stakeholders (Section 4.2.2), it is important to provide representations of the prioritized possible causes of a hazard (i.e., MCSs), SPoF that may cause a hazard, the combination of failures that may cause a hazard (i.e., MCSs), failures with larger impact on the hazard's safety (i.e., BEs), suggestions for increasing the hazard's safety, the hazards' safety evolution after system improvements, the safety level of the hazard being analyzed, generated information from MCS analysis, and properties of the system components related to the failures. However, all proposed information is asked for by at least 3 stakeholders of the respondents.

The *hazard size* can be grouped according to its number of MCSs and its number of BEs: small hazards have in the order of magnitude of 10 MCSs or 10 BEs, medium having 100 MCSs or [100-1000[BEs, and large having 1000 MCSs or [1,000-10,000[BEs.

Our respondents have worked with different *sizes of hazards* in the range of [1-30 to 10,000-100,000] MCSs. This broad range is explained by the workplace of the respondents. Participants who worked with smaller hazards are working at a university, therefore, dealing with smaller systems, while the others are working in industry and at research institutes, thus, working with larger systems.

The *time needed to compare two hazards* of an average size (medium) regarding their single points of failure (SPoF) ranges from 5 minutes to 2 days. This means the respondents are using different tools with different facilities. However, because the time spent for comparing only two hazards reaches up to 2 days, there is a need for better visualizations to support this task and reduce the time and the effort spent by the analysts.

The most used *tools for MCS analysis* by the respondents are: ESSaRel followed by FaultTree+, BlockSim, and RiskSpectrum. The same tools are considered to be the *best tools currently used*. Grouped by working environment, the best tool used in industry is RiskSpectrum, at the university the best tools are ESSaRel, BlockSim, and FaultTree+, and at research institutes the best tools are ESSaRel and FaultTree+.

The estimation of the *time spent for performing MCS analysis* tasks was only provided by four participants (the question was not mandatory). These participants were using FaultTree+, ESSaRel, MagicDraw, and C^2FT. Even if these tools are considered being used, the participants spend a long time (i.e., several days) performing MCS analysis tasks for medium (i.e., order of magnitude: 100 MCSs) and large hazards (i.e., order of magnitude: 1000 MCSs). This highlights the need for better visualizations in order to reduce the time and effort spent on MCS analysis.

5.2 RQ-2: Requirements of the Safety Engineers for Performing MCS Analysis

The *most necessary information* for the participants for performing MCS analysis is: SPoF, MCSs' order, BEs with high FP, the system components related to the BEs, BEs with high number of occurrence, FP of the hazards, FP of the MCSs and BEs, MCSs with a high FP, and the system components properties. Surprisingly, the total number of BEs and the total number of MCSs were not considered to be necessary even though there is an inverse relationship between each of these two and the hazard's safety (if all other factors are fixed).

Four participants reported they *need additional information* for performing MCS analysis. The only two related to MCS analysis are: the information about the architectural components providing the largest amount of basic failures or MCS, and dependency matrices. There are five cases possible for a dependency matrix related to this study. These cases are a dependency matrix between: BEs, BEs and physical components, MCSs, MCSs and physical components, and BEs and MCSs. All other additional information reported either refers to higher level analysis tasks comprising MCS analysis (i.e., fault tree analysis, hazard analysis, risk analysis) or to other types of analysis (i.e., minimal path set (MPS) analysis, sensitivity, and uncertainty analysis) that are not in the focus of this study.

Regarding *MCS analysis tasks*, the participants considered 13 out of 17 tasks (removed duplicates) to be needed during performing MCS analysis. From these four tasks the two: "to prioritize MCSs for detailed analysis" and "to know the BEs with high FP" are not consistent with answers to other questions of the questionnaire where they are considered to be important tasks. The reason is probably that these two points in the question were negated and the participants did not negate their answers accordingly. All other answers are consistent across the different questions . Therefore, the tools used for performing MCS analysis should provide the capability of performing these tasks efficiently.

5.3 RQ-3: Quality of Current Tools for Performing MCS Analysis as Perceived by the Safety Engineers

With regard to the *practitioners' perception of the quality of information representation:* The participants rate the information generated by the best tool they currently use for performing MCS analysis as *understandable*. Since the respondents rate the *quality of the information* *representation* as fair, where fair is the midpoint of the ratings, improving current representations (currently mostly in textual and tabular form) or adding new ones is highly recommended.

The respondents consider FaultTree+, BlockSim, and ESSaRel being the most powerful tools in their ability of providing the *information in one sight*. However, since the ability of the other tools is limited, there should be improvements on the representations of “BEs’ number of occurrence”, “safety level of the hazard being analyzed”, “MCSs effected by a BE”, and “System design”, followed by “MCSs with low order” and “MCSs with SPoF”.

RQ-3b *Practitioners’ Perception of the Quality of Interaction Capabilities:* From the point of view of the respondents, the most powerful tools providing the *interaction capability of sorting* all information other than “both BE’s FP and BE’s number of occurrence” are RiskSpectrum, FaultTree+, and BlockSim. All other tools provide the sorting for only 2 out of 6 options mentioned in the questionnaire. Therefore, the interaction capability for sorting the BE’s FP, BE’s number of occurrence, both BE’s FP and number of occurrence, and both MCS’s FP and order should be added to the tools, according to the requirements.

Surprisingly, from the point of view of the respondents, there is only one tool that can provide the *interaction capability of filtering* all of the 4 options provided in the questionnaire, namely WinNUPRA. According to the requirements, filtering by MCS FP, MCS order, BE FP, and BE number of occurrence are very important interaction features that should be added to the tools for supporting MCS analysis.

Finally, the *amount of interaction regarding scrolling up/down in the same view* is found to be “too much” and should be reduced.

RQ-3c *Practitioners’ Perception of Usability:* From the point of view of most of the respondents the best tool they are currently using has a good *usability*. Nevertheless, there were 2 points that the participants were unsure of: the ease of use of the tools and whether the tools support them in communicating with their stakeholders.

Since all other points regarding the ease of use are ranked positively, the reason is probably that the statement of the ease of use was negated and the participants did not negate their answers accordingly.

Thus, the only point that the respondents were unsure of is whether the tools support them in communicating with the stakeholders. Therefore, it is advisable to develop improved visualizations or suitable environments to support this communication.

RQ-3d*: Level of Satisfaction with Current Tools for Performing MCS Analysis:* The *satisfaction level* of most participants is positive regarding the best tool they are currently using for performing MCS analysis.

Finally, most participants prefer *2D over 3D interaction* when analyzing MCSs. One reason of such a preference might be that they are used to working in 2D environments.

6 FINDINGS

The results of this study show, that MCS analysis is performed for a large amount of purposes, and thus the results confirm the importance of MCS analysis for safety analysis. However, we found some unexpected results that are reported next. Moreover, we derive recommendations for improving the safety tools to support MCS analysis.

Unexpected Results: There were two unexpected results of this study. The results show, that classifying MCSs regarding their FPs is a task that is rarely performed by the participants even though it helps in identifying weak points of a top level event of a system (**RQ-1**). Surprisingly, the total number of BEs and the total number of MCSs were not considered to be necessary even though there is an inverse relationship between each of these two and the hazard's safety (fixing all other factors, **RQ-2**).

Recommendations for Tool Improvements: The tools should provide and adequately represent: BEs with high FP, system components related to BEs, BEs with high number of occurrence, properties of system components, and dependency matrices (**RQ-2**). Further, the most important need (**RQ-3**) is to improve the representation for gaining immediate insight regarding the BEs' number of occurrence, the safety level of the hazard being analyzed, the MCSs effected (and their quality) by a BE, MCSs with SPoF, and the system design (i.e., physical parts). Regarding interaction, sorting by BE's FP, BE's number of occurrence, both BE's FP and number of occurrence, and both MCS's FP and order, should be provided by the tools, according to the requirements (**RQ-3**). Moreover, filtering by MCS FP, MCS order, BE FP, and BE number of occurrence is a very important interaction feature lacking in many of the tools, and thus, should be added to the tools for supporting MCS analysis (**RQ-3**). Finally, the amount of interaction regarding scrolling up/down in the same view is found to be too much and should be reduced.

Although the high usability rating of the tools, these tools do not support the communication between the safety analysts and their stakeholders. Therefore, visualizations beyond text and tables should be introduced to support this communication.

Surprisingly, the time estimation for comparing two hazards of an average size (medium) regarding their single points of failure reaches up to two days (**RQ-1**). This is a long time and implies a large effort spent on this task. Additionally, the time spent to perform MCS analysis tasks in general is up to several days, even for hazards having an order of magnitude of 100s MCSs (medium size, **RQ-1**). As most information generated by MCS analysis is represented in text and tables, the recommendation is as well to use new visualizations in order to reduce the amount of time and effort spent in exploring and searching for the relevant information.

As expected, 2D interaction is preferred over 3D interaction for interacting with the generated information from MCS analysis (**RQ-3**).

7 THREATS TO VALIDITY

Content validity: To improve content validity, we performed peer reviews with experts from empirical research, safety analysis, and visualization. Additionally, we used standardized instrument for measuring the practitioners' perception of usability, namely the Technology Acceptance Model [32]: p. 448.

Response rate: To increase the response rate, we followed the recommendations of Cleeland et al. [9], DeMaio at al. [10], and [23]. The final response rate was 45%. This is considered high in case of online surveys. The average time for answering the survey was 26 minutes (SD = 17 minutes). Respondents did not interrupt the questionnaire or had time to talk to colleagues about it. Thus, there is no history of maturation bias possible.

Representative sample: We used a purposive sample. The demographic analysis of the respondents shows that they are representative of the target population. All participants are experienced in MCS analysis and in using tools for performing MCS analysis. However, the generalization of the results requires a replication of the survey with a larger sample of safety engineers. Overall, we conclude that there is no socially desirable responding bias and that the answers mirror the participants' insights.

Section/Question completion rate: We aimed at increasing the sections and questions completion by adding filters. Only one respondent did not complete the survey. Therefore, the corresponding responses were not included in the analysis. The participants answered all mandatory questions (31 from 36 for survey I, 32 from 37 for survey II). Optional questions (5) were intended to give the opportunity to comment mandatory questions. Thus, the non-observation bias is low.

Hawthorne effect: To avoid that participants answered questions randomly, we included duplicated and rephrased questions. The analysis of these questions shows that their answers are mostly consistent. Further, we checked whether the participants were always marking left or right extreme or the middle of the options (controlled integrity). That was not the case.

8 CONCLUSION

We aimed at (1) exploring the state of the practice regarding Minimal CutSet (MCS) analysis from the perspective of practitioners, i.e., safety engineers and (2) identifying gaps in the representation of the important information used for MCS analysis. Furthermore, this research is intended for transferring the knowledge of the safety to the visualization domain to provide a better understanding, and guide the development of MCS analysis tools and visualizations. An online survey was used to gain as many replies as possible from experienced people in MCS analysis from different working environments who use safety tools for performing the analysis. This study determined important tasks performed during MCS analysis, its purposes, the requirements of the analysts, hazard sizes being confronted with, and the stakeholders benefiting from the results of MCS analysis. Moreover, it contributes to identify the improvements needed: integrating new or improved visualizations while preserving the 2D interactions. Finally, we identify the need of replicating this survey with a larger sample in order to get a better understanding of MCS analysis needs in specific safety domains and identifying commonalities and variability across different domains.

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References

[1] Yasmin I. Al-Zokari, Liliana Guzman, Dirk Zeckzer, and Hans Hagen, 2012. `http://www.irtg.uni-kl.de/~alzokari/Demos/MyDemos.html`.

[2] Yasmin I. Al-Zokari, Taimur Khan, Daniel Schneider, Dirk Zeckzer, and Hans Hagen. CakES: Cake Metaphor for Analyzing Safety Issues of Embedded Systems. In Hans Hagen, editor, *Scientific Visualization: Interactions, Features, Metaphors*, volume 2 of *Dagstuhl Follow-Ups*, pages 1–16. Schloss Dagstuhl–Leibniz-Zentrum fuer Informatik, 2011.

[3] Yasmin I. Al-Zokari, Daniel Schneider, Dirk Zeckzer, Liliana Guzman, Yarden Livnat, and Hans Hagen. Enhanced CakES representing Safety Analysis results of Embedded Sys-

tems. In *Federated Conference on Computer Science and Information Systems (FedCSIS), RAMSS track*, 2011.

[4] Yasmin I. Al-Zokari, Daniel Schneider, Dirk Zeckzer, and Hans Hagen. An Enhanced Slider for Safety Analysis. In *IEEE VisWeek Poster*, 2011.

[5] Yasmin I. Al-Zokari, Dirk Zeckzer, Peter Dannenmann, Liliana Guzman, and Hans Hagen. Evaluation of “Safety-Domino”: a Graphical Metaphor for Supporting Minimal Cut Set Analysis. *IADIS International Journal on Computer Science and Information Systems, online journal*, 7:129–151, 2012.

[6] Marco Bozzano and Adolfo Villafiorita. *Design and Safety Assessment of Critical Systems.* CRC Press (Taylor and Francis), an Auerbach Book, 2010.

[7] Marko Cepin. DEPEND-HRA-A method for consideration of dependency in human reliability analysis. *Reliability Engineering & System Safety*, 93(10):1452–1460, 2008.

[8] Jason Cleeland, Carsten Schmitz, Thibault Le Meur, Marcel Minke, David Olivier, and Thomas White. LimeSurvey: Features. `http://www.limesurvey.org/en/about-limesurvey/features`; Online; accessed 31-Jan-2012.

[9] Jason Cleeland, Carsten Schmitz, Thibault Le Meur, Marcel Minke, David Olivier, and Thomas White. LimeSurvey: Question Types. `http://docs.limesurvey.org/Question+types`; Online; accessed 31-Jan-2012.

[10] Theresa J. DeMaio, Jennifer Rothgeb, and Jennifer Hess. Improving Survey Quality Through Pretesting, 1998.

[11] Nasser S. Fard. Determination of minimal cut sets of a complex fault tree. *Comput. Ind. Eng.*, 33(3–4):59–62, December 1997.

[12] N.S. Fard and T.H Lee. Cutset enumeration of network systems with link and node failure. *Reliability Engineering & System Safety*, 65:141–146, 1999.

[13] J. B. Fussell and W. E. Vesely. A New Methodology for Obtaining Cut Sets for Fault Trees. *Transactions American Nuclear Society*, 15(1):262–263, 1972.

[14] Stian Høiset and Eli Glittum. Risk and Safety Training Using Virtual Reality (VR-Safety). In *SPE International Conference on Health, Safety, and Environment in Oil and Gas Exploration and Production.* Society of Petroleum Engineers, April 2008. `http://www.cmr.no/cmr_computing/index.cfm?id=179523`.

[15] IBM. SPPS Statistics 17. `http://www.ibm.com/software/de/analytics/spss/`.

[16] IBM. Transform to an on demand business thru IBM Business Integration Solution, 2007. `www-07.ibm.com/hk/events/2007/09_csolution/downloads/TransformtoanondemandbusinessthruIBMBusinessIntegrationSolution.pdf`.

[17] Fraunhofer Institute. Virtual and Augmented Reality for Maximum Embedded System Safety, Security and Reliability (ViERforES). `http://www.iff.fraunhofer.de/en/research-network/vierfores.html`.

[18] Taimur Khan, Daniel Schneider, Yasmin Al-Zokari, Dirk Zeckzer, and Hans Hagen. Framework for Comprehensive Size and Resolution Utilization of Arbitrary Displays. In Hans Hagen, editor, *Scientific Visualization: Interactions, Features, Metaphors*, volume 2 of *Dagstuhl Follow-Ups*, pages 144–159. Schloss Dagstuhl–Leibniz-Zentrum fuer Informatik, 2011.

[19] Christoph Lauer, Reinhard German, and Jens Pollmer. Fault tree synthesis from UML models for reliability analysis at early design stages. *SIGSOFT Softw. Eng. Notes*, 36(1):1–8, January 2011.

[20] Hung-Yau Lin, Sy-Yen Kuo, and Fu-Min Yeh. Minimal Cutset Enumeration and Network Reliability Evaluation by Recursive Merge and BDD. In *Proceedings of the Eighth IEEE Symposium on Computers and Communications (ISCC 2003)*, pages 1341–1346, 2003.

[21] Y. Papadopoulos, J. McDermid, R. Sasse, and G. Heiner. Analysis and synthesis of the behaviour of complex programmable electronic systems in conditions of failure. *Reliability Engineering & System Safety*, 71(3):229–247, 2001.

[22] S. A. Patterson and G. E. Apostolakis. Identification of critical locations across multiple infrastructures for terrorist actions. *Reliability Engineering & System Safety*, 92(9):1183–1203, 2007.

[23] QuestionPro Online Survey Software. 10 Easy Ways to Increase Response Rates for your Online Survey, 2012. `http://www.questionpro.com/a/showArticle.do?articleID=deploy01`.

[24] J. Russell. *Exploring Psychology: AS Student Book for AQA A*. Exploring Psychology. OUP Oxford, 2008. `http://books.google.de/books?id=4ereiHom3d8C`.

[25] E. O. Schweitzer, Bill Fleming, Tony J. Lee, and Paul M. Anderson. Reliability Analysis of Transmission Protection Using Fault Tree Methods. In *Proceedings of the 24th Annual Western Protective Relay*, 1997.

[26] Robert F. Szafran. *Answering Questions With Statistics*. SAGE Publications, 2011. `http://books.google.de/books?id=GEJTD6kr08oC`.

[27] A. Thums and G. Schellhorn. Formal Safety Analysis in Transportation Control. In *Proceedings of the Workshop on Software Specification of Safety Relevant Transportation Control Tasks*, 2002.

[28] Edward R. Tufte. *Visual explanations: images and quantities, evidence and narrative*. Graphics Press, Cheshire, CT, USA, 1997.

[29] Edward Rolf Tufte. *The visual display of quantitative information*. Graphics Press, 1992.

[30] J. Utts and R. Heckard. *Statistical Ideas and Methods*. Cengage Learning, 2005.

[31] Jørn Vatn. Finding minimal cut sets in a fault tree. *Reliability Engineering & System Safety*, 36(1):59–62, January 1992.

[32] Viswanath Venkatesh, Michael G. Morris, Gordon B. Davis, and Fred D. Davis. User acceptance of information technology: Toward a unified view. *MIS Quarterly*, 27(3):425–478, 2003. `http://www.jstor.org/stable/30036540`.

[33] Matthew Ward, Georges Grinstein, and Daniel A. Keim. *Interactive Data Visualization: Foundations, Techniques, and Application*. A.K. Peters, Ltd, May 2010.

[34] Claes Wohlin, Per Runeson, Martin Höst, Magnus C. Ohlsson, Björn Regnell, and Anders Wesslén. *Experimentation in Software Engineering*. Computer Science. Springer, 2012.

[35] Yi Yang, Patric Keller, and Peter Liggesmeyer. Visual Approach Facilitating the Importance Analysis of Component Fault Trees. In Frank Ortmeier and Peter Daniel, editors, *Computer Safety, Reliability, and Security - SAFECOMP 2012*, volume 7613 of *Lecture Notes in Computer Science*, pages 486–497, Berlin/Heidelberg, Germany, 2012. Springer.

[36] Yi Yang, Patric Keller, Yarden Livnat, and Peter Liggesmeyer. Improving Safety-Critical Systems by Visual Analysis. In Christoph Garth, Ariane Middel, and Hans Hagen, editors, *Proceedings of IRTG 1131 Workshop 2011*, volume 27 of *OpenAccess Series in Informatics (OASIcs)*, pages 43–58, 2012.

[37] Yi Yang, Dirk Zeckzer, Peter Liggesmeyer, and Hans Hagen. ViSSaAn: Visual Support for Safety Analysis. In Hans Hagen, editor, *Scientific Visualization: Interactions, Features, Metaphors*, volume 2 of *Dagstuhl Follow-Ups*, pages 378–395. Schloss Dagstuhl–Leibniz-Zentrum fuer Informatik, 2011.

[38] Wei-Chang Yeh. An improved algorithm for searching all minimal cuts in modified networks. *Reliability Engineering & System Safety*, 93(7):1018–1024, 2008.

[39] Wei-Chang Yeh. A simple minimal path method for estimating the weighted multi-commodity multistate unreliable networks reliability. *Reliability Engineering & System Safety*, 93(1):125–136, 2008.

[40] T. Yuge and S. Yanagi. Quantitative analysis of a fault tree with priority AND gates. *Reliability Engineering & System Safety*, 93(11):1577–1583, 2008.

[41] Tan Z. Minimal cut sets of s-t networks with k-out-of-n nodes. *Reliability Engineering & System Safety*, 82(1):49–54, 2003.

[42] E. Zio, M. Librizzi, and G. Sansavini. Determining the minimal cut sets and fussell-vesely importance measures in binary network systems. *Reliability Engineering and System Safety*, pages 723–729, 2006.