NTNU – Trondheim
Norwegian University of
Science and Technology

Formal Safety Assessment of an Open Loop System

Mari Løvald Andresen

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Supervisor: Bjørn Egil Asbjørnslett, IMT

Norwegian University of Science and Technology
Department of Marine Technology

PREFACE

This master thesis represents the final result of an integrated Master of Science within the study programme Marine Technology at the Norwegian University of Science and Technology (NTNU) and corresponds to 30 credits. The thesis is written by Mari Løvald Andresen during the spring semester 2015.

The master thesis is the continued work of a project thesis written in the autumn semester 2014, which was a literature study on exhaust gas cleaning systems, also known as scrubbers. Additionally, the Technology Qualification Process given by DNV GL was elaborated, together with a qualification process of an open loop system manufactured by Wärtsilä, which resulted in a FMECA and a risk matrix. The objective of this master thesis was to continue the study of the open loop system to gain a greater understanding on the challenges this technology has in regards to system risks and safety. The study is executed by adopting the risk assessment method Formal Safety Assessment (FSA).

The motivation of the study was because of the scrubber technology recently has been introduced in the maritime industry, and there is fluctuating opinions whether the technology meets the strict sulphur regulations or not. There exist few published studies involving exhaust gas cleaning systems, regarding their issues and risks. A major challenge in the work was to obtain reliable literature, as well as finding the limited quantity of relevant literature studies on the field. This was especially demanding when evaluating the risks quantitatively along the Formal Safety Assessment (FSA). Both uncertainties and probabilities on components were assumed based on previous experiences in environments other than exhaust gas cleaning systems. However, the main objective was to map the challenges this technology has in relation to risks.

I wish to thank Professor Bjørn Egil Asbjørnslett at the Department of Marine Technology, NTNU, for giving guidance during master thesis execution. Lastly, a special thanks to PhD Candidate Christoph Alexander Thieme at the Department of Marine Technology, NTNU, for providing comprehensive information regarding software CARA-FaultTree.

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Mari Løvald Andresen

ABSTRACT

Shipping burns approximately 300 million tonnes of fuel per year, and 12 million tonnes of sulphur oxides (SO_x) are emitted, annually. The International Maritime Organization (IMO) set the standards for the safety, security and environmental performance of international shipping, globally and have even stricter standards in Emission Control Areas (ECAs). The maritime industry is facing challenges in meeting imposed requirements given by IMO. Among others, Regulation 14 in MARPOL Annex VI sets limitations on sulphur oxides and particulate matter. On and after January 1st 2020 the sulphur content of any fuel oil used onboard ship shall not exceed 0.50% m/m. However, the implementation date is to be reviewed in 2018 to see if the limit is achievable within the set time frame. Besides, on and after January 1st 2015 the sulphur content of any fuel oil used onboard ship shall not exceed 0.10% m/m in ECA.

Exhaust gas cleaning systems, also known as scrubbers, have extensive land-bases experience. Regulation 4 in MARPOL Annex VI states that it is allowed to use an alternative compliance method which is at least as effective in terms of emission reductions as required in MARPOL Annex VI, and the standards in Regulation 14. Hence, *2009 Guidelines for Exhaust Gas Cleaning Systems* (i.e. MEPC.184(59)) was adopted on July 17th 2009 by IMO, where the intention is to specify the requirements for the testing, survey, certification, and verification of scrubbers.

The objective of this master thesis was to evaluate an open loop system through Formal Safety Assessment to gain greater understanding on the challenges this technology has in relation to system risks and safety. The Formal Safety Assessment is a new approach in the maritime industry, and can be used as a tool to help evaluate new regulations or to compare proposed changes within existing standards. The technique consists of five steps: identification of hazards, risk analysis, risk control options (RCOs), cost-benefit assessment, and recommendations for decision-making.

All steps of the Formal Safety Assessment were carried out on an open loop system manufactured by Wärtsilä. The basis of the assessment was a preliminary version of a P&ID of the open loop system, which was further simplified by the author. The qualitative (e.g. failure modes, failure causes) and quantitative (i.e. λ/E6, MTTR) inputs through the analysis were extracted from the handbook *Offshore Reliability Data* (OREDA).

A FMECA and a risk matrix were created in the first step to identify hazards. Risk Control Tree (RCT) was modelled in the second step, where the material from the first step was evaluated quantitatively. In the third step, the results from the second step were utilised to propose effective and practical risk control measures of the given open loop system. Benefits and costs associated with implementing the risk control options were identified and compared in the fourth step. Finally, recommendations for decision-making were determined on the basis of the previous steps.

On the grounds of 153 cases of components with a specific failure mode in the FMECA, 52% are ranked with low risk, 45% with medium risk, and 3% with high risk. The scrubber system has the highest risk within medium and high risk, where the drainpipe and the injection nozzles are the most critical components. The modelled Risk Contribution Tree (RCT) consists of six fault trees and three event trees, distributed within three accident categories (i.e. Overpressure, Hazards related to loading/discharging operations, Purification failure). The fault trees were constructed and quantitatively analysed in software CARA-FaultTree. The observations showed that the most critical top events are overpressure in scrubber device and venturi, and difficulties with purifying washwater. The end events with high material damage in the event trees have relatively low frequencies per year, as an effect of reliable safety systems within the scrubber system and low frequencies of the initiating events. The following risk control options increase the reliability of the open loop system: improvement of corrective maintenance, review the preventive maintenance procedures, redundancy in inlet monitor and outlet monitor, and reinforcement of joints between nozzles, pipelines and scrubber casing. In a cost-benefit aspect, redundancy of monitors and reinforcement of joints are the most beneficial solutions to increase the open loop system's reliability in a feasible and safe matter.

Based on the results from the Formal Safety Assessment, it is concluded that the open loop system is considered to be highly reliable. However, with improvement of risk control options, as additional monitors and reinforcement of joints inside the scrubber device, the system increases its availability significantly. The adoption will increase the time of operation of the system, and assist the system to meet the guidelines in resolution MEPC.184(59). The results are applicable for shipowners, class societies, and manufactures. By knowing the critical components, the open loop system(s) can increase operation performance and reliability. The perfections are especially of great importance since the purpose of scrubbers is to meet the imposed limitations on sulphur oxides.

SAMMENDRAG

Shipping forbrenner ca. 300 millioner tonn drivstoff per år og 12 millioner tonn svoveloksider (SO_x) slippes ut årlig. Den Internasjonale Skipsfartsorganisasjonen (IMO) setter standarder for å ivareta sikkerhet til sjøs og jobber for å forhindre forurensning av det maritime miljøet, både globalt og spesielt i såkalte Emission Control Areas (ECA-er). Den maritime næringen står ovenfor utfordringer i møte med pålagte krav, gitt av IMO. Forskrift 14 i MARPOL Annex VI setter begrensinger av utslipp av svoveloksider og svevestøv. Fra og med 1. januar 2020 skal ikke svovelinnholdet i brensel ombord på skip overstige 0,50 % m/m. Det må påpekes at gjennomføringsdatoen skal vurderes i 2018 for å se om grensen er oppnåelig på så kort tidsrom. Foruten skal ikke svovelinnholdet i brensel ombord på skip overstige 0,10 % m/m i Emission Control Areas fra og med 1. januar 2015.

Exhaust gas cleaning systems som også kjennetegnes som scrubbere, har omfattende referanser fra landbasert industri. Forskrift 4 i MARPOL Annex VI erklærer at det er tillatt å bruke alternative metoder som er minst like effektive og som oppfyller utslippsreduksjonskravene. Det ble derfor vedtatt retningslinjer for scrubbere den 17. juli 2009 av IMO i resolusjonen *2009 Guidelines for Exhaust Gas Cleaning Systems (*MEPC.184(59)). Intensjonen med retningslinjene er å spesifisere krav til testing, undersøkelser, sertifisering, samt verifisering av scrubbere.

Formålet med denne masteren var å evaluere et open loop system gjennom Formal Safety Assessment for å øke forståelsen for de utfordringene i scrubber-teknologien har i forhold til systemrisiko og sikkerhet. Formal Safety Assessment er en ny tilnærming i den maritime næringen, og kan brukes som et verktøy til å vurdere nye forskrifter eller sammenligne foreslåtte endringer med eksisterende standarder. Fremgangsmåten består av fem trinn: identifikasjon av farer, risikoanalyse, risikokontroll alternativer, kost-nytte analyse og anbefalinger til beslutningstaker.

Alle trinnene i Formal Safety Assessment ble gjennomført under evaluering av et open loop system produsert av Wärtsilä. Grunnlaget for analysen var en foreløpig versjon av en P&ID over systemet, samt ytterligere forenklinger av forfatteren. Kvalitativ informasjon som feilmoduser og årsaker til feil, og kvantitative data som for eksempel λ/E6 og MTTR i analysen er hentet fra håndboken *Offshore Reliability Data* (OREDA).

En FMECA og en risikomatrise ble opprettet i det første trinnet for å identifisere farer. Et Risk Control Tree (RCT) ble modellert under trinn nummer to der resultatene fra trinn en ble

vurdert kvantitativt. I det tredje trinnet ble resultatene fra trinn to anvendt for å foreslå effektive og praktiske risikokontroll alternativer av det gitte systemet. Videre ble de foreslåtte alternativer vurdert i en kost-nytte analyse under det fjerde trinnet. Avslutningsvis ble anbefalinger for beslutninger fastsatt på grunnlag av funnene i de tidligere trinnene.

Ut ifra 153 tilfeller av komponenter med en spesifikk feilmodus i FMECA-en er 52 % rangert med lav risiko, 45 % med middels risiko og 3 % med høy risiko. Scrubber-systemet har høyest risiko av middels og høy risikograd, hvor avløpet fra scrubber-enheten og innsprøytingsdysene er de mest kritiske komponentene. Det modellerte Risk Contribution Tree består av seks feiltrær og tre hendelsestrær fordelt innen tre ulykkeskategorier (overtrykk, farer knyttet til lasting/lossing og rensevikt). Feiltreene ble konstruert og analysert i programvaren CARA-FaultTree. Observasjonene viser at de mest kritiske topphendelsene er overtrykk i selve scrubber-enheten og venturien og det kan forekomme vanskeligheter med å rense spylevann. Endehendelsene med høye materielle skader i hendelsestrærne har relativet lave frekvenser per år, noe som er en effekt av pålitelige sikkerhetssystemer i systemet og initierende hendelser med lave frekvenser. De følgene risikokontroll alternativene øker påliteligheten av systemet: forbedring av korrektivt vedlikehold, gjennomgang av rutinene for forebyggende vedlikeholdsarbeid, redundans i inngang- og utgangs overvåkningsapparater og forsterkning av skjøtene mellom innsprøytingsdysene, rør og innfatningen til scrubber-enheten. Kost-nytte analysen viser at de to sistnevnte risikokontroll alternativene er de mest fordelaktige løsningene for å kunne øke systemets pålitelighet på en gjennomførbar og trygg måte.

På grunnlag av resultatene fra Formal Safety Assessment er det konkludert med at open loop systemet er ansett for å være svært pålitelige. Men med forbedring av risikokontroll alternativer, som ekstra overvåkningsapparater og forsterkning av skjøter på innsidene av scrubber-enheten, øker tilgjengeligheten til systemet betraktelig. Innføringen vil øke operasjonstiden av systemet, og sikre at systemet er i samsvar med retningslinjene i resolusjonen MEPC.184(59). Resultatene kan være nyttige for rederier, klasseselskap og produsenter. Både drifts ytelse og pålitelighet øker ved å ha kjennskap til de mest kritiske komponentene, og et fullkomment open loop system er spesielt viktig med på tanke på at hensikten med et scrubber-system er å nå utslippskravene på svoveloksider.

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ABBREVIATIONS

ABS	American Bureau of Shipping
CAF	Cost of Averting a Fatality
CAPEX	Capital Expenditure
DNV GL	Det Norske Veritas and Germanischer Lloyd
ECA	Emission Control Area
ETA	Event Tree Analysis
ETM	Technical Manual
FMEA	Failure Mode and Effects Analysis
FMECA	Failure Mode Effect and Criticality Analysis
FSA	Formal Safety Assessment
FTA	Fault Tree Analysis
ICAF	Implied Cost of Averting a Fatality
IMO	International Maritime Organization
LNG	Liquefied Natural Gas
MARPOL	International Convention for the Prevention of Pollution from Ships
MOCUS	Method for Obtaining Cut Sets
MTBF	Mean Time Between Failure
MTTF	Mean Time To Failure
OMM	Onboard Monitoring Manual
OREDA	Offshore Reliability Data
P&ID	Piping and Instrument Diagram
PAH	Polycyclic Aromatic Hydrocarbons
R&M	Repairs and Maintenance
RCO	Risk Control Option
RCT	Risk Contribution Tree
SECC	SO_x Emission Compliance Certificate
SECP	SO_x Emission Compliance Plan

1 INTRODUCTION

1.1 BACKGROUND

Shipping burns approximately 300 million tonnes of fuel per year, and 12 million tonnes of sulphur oxides (SO_x) are emitted, annually (Balland 2014a). The International Maritime Organization (IMO) set the standards for the safety, security and environmental performance of international shipping, globally and have even stricter regulations in Emission Control Areas (ECAs) (IMO 2014). The maritime industry is facing challenges meeting the imposed requirements given by IMO. Among others, Regulation 14 in MARPOL Annex VI sets limitations on sulphur oxides and particulate matter. On and after January 1st 2020 the sulphur content of any fuel oil used onboard ship shall not exceed 0.50% m/m. However, the implementation date is to be reviewed in 2018 to see if the limit is achievable within the set time frame. Besides, on and after January 1st 2015 the sulphur content of any fuel oil used onboard ship shall not exceed 0.10% m/m in ECA (Balland 2014a).

1.1.1 EXHAUST GAS CLEANING SYSTEMS

Exhaust gas cleaning systems, also known as scrubbers, have extensive land-bases experience (Balland 2014b). Regulation 4 in MARPOL Annex VI states that it is allowed to use an alternative compliance method which is at least as effective in terms of emission reductions as required in MARPOL Annex VI, and the standards in Regulation 14. Hence, 2*009 Guidelines for Exhaust Gas Cleaning Systems* was adopted on July 17th 2009 by IMO, where the intention is to specify the requirements for the testing, survey, certification, and verification of scrubbers (IMO 2009b).

Scrubbers are one of four solutions for a vessel to meet the new requirements. Liquefied Natural Gas (LNG), fuel switch, and to avoid the stricter areas, are the three residual ones (Balland 2014b). DNV GL claims a scrubber is often the most cost-efficient solution, and effectively removes sulphur oxides (SO_x) and particular matter (PM) under the right conditions compared to the other technical solutions. Alpha Laval Aalborg state that their scrubber systems, regardless on type, removes 98% SO_x from the exhaust (ABS 2013). According to American Bureau of Shipping (ABS), scrubbers can be effective in fulfilling the regulations of not exceed 0.5% sulphur content. However, there are uncertainties to whether some scrubbers have the ability to provide equivalent SO_x emissions to 0.1% (ABS 2013).

One or several scrubber are installed in the exhaust gas system after the engine or boiler. The principle is that the sulphur content in the exhaust gas gets ¨washed¨ with a variety of substances including seawater, chemically treated fresh water or dry substances in a scrubber device (ABS 2013). Today, there are two basic concepts of scrubbers, dry systems and wet systems. A dry scrubber exposes hydrated lime-treated granulates as absorbent instead of seawater or other types of liquid. There are three types of wet scrubbers: open loop system, closed loop system, and hybrid system. An open loop system makes use of seawater to react with the SO_x content in the exhaust gas, and discharges the water back to the sea after residual treatment. Since the system utilises seawater as scrubber medium, the scrubbing process relies upon the buffering capacity of the water, also known as alkalinity and salinity. The capacity of the seawater affects the ability of the scrubbing water to neutralize the acids scrubbed from the exhaust gas. Therefore, the scrubber performance depends the location, time of year, and proximity to the coastal regions where the vessel is sailing. In a closed loop system the water treatment is closed and the water is circulating through the scrubber process independent of the chemistry of the waters. Moreover, a hybrid system is a combination of the open loop system and closed loop system (ABS 2013, Wärtsilä 2014).

Statistics from DNV GL December 2014 shows that the numbers of ships installing one or several scrubbers are increasing. In 2012 fewer than 30 ships had installed one or several scrubbers. By 2014, the numbers reached more than 60, and in 2018 it is assumed that almost 200 classified ships by DNV GL have installed one or several scrubbers. Furthermore, information from DNV GL's fleet displays it is more common to retrofit ships and install scrubbers than installing scrubbers on newbuilds. Hybrid scrubber systems, followed by open and closed loop systems, have recently been the most customary type of scrubber. It appears that cruise ships/ferries, RO-RO vessels, and general cargo are the largest consumers of scrubber systems (DNV GL 2014). The information given by DNV GL is found in Appendix A.

Regulation 3.1 in MARPOL Annex VI (Prevention of Air Pollution from Ships) addresses exceptions and exemptions for ships experiencing noncompliance with the emission standards in MARPOL VI Regulation 14 as a result of damage to the ship or its equipment. The exemption is accepted or declined by the concerned flag Administrations. To get an acceptance, the shipowner has to provide evidence that significant design and operation (i.e. sufficient redundancy) has been incorporated in the system (ABS 2013).

1.1.2 RESOLUTION MEPC.184(59)

As previous mentioned, *2009 Guidelines for Exhaust Gas Cleaning Systems*, also referred to as resolution MEPC.184(59), was adopted on July 17th 2009 by IMO. Note, these guidelines are not regulations. Though, an installed exhaust gas cleaning system that meets the guidelines will be accepted as equivalent by the Administrations (i.e. flag state). The purpose with the guidelines is to be objective and performance oriented. A scrubber system may be approved by periodic parameters and emission checks, or the system may be equipped with a continuous emission monitoring system. Ratio emission SO_2 (ppm)/CO_2 (%) is an utilised method, which simplifies the monitoring of SO_x emission and assists approval of a scrubber system. Table 1.1 lists the fuel oil sulphur limits recorded in Regulations 14.1 and 14.4 and corresponding to emissions values (IMO 2009a).

Table 1.1: Fuel oil sulphur limits recorded in regulations (IMO 2009a)

Fuel Oil Sulphur Content (% m/m)	Ratio Emission SO_2 (ppm)/CO_2 (% v/v)
4.50	195.0
3.50	151.7
1.50	65.0
1.00	43.3
0.50	21.7
0.10	4.3

The guidelines allow two different schemes: Scheme A and Scheme B. Scheme A deal with unit certification with parameter and emission checks, while Scheme B regards continuous emission monitoring with parameter checks. Both of them require the following documentations:

- SO_x Emission Compliance Plan (SECP)
- Onboard Monitoring Manual (OMM)
- EGC Record Book or Electronic Logging System

The difference between the two schemes is that Scheme A also includes SO_x Emissions Compliance Certificate (SECC) and Technical Manual for Scheme A (ETM Scheme A), while Scheme B includes Technical Manual for Scheme B (ETM Scheme B) (IMO 2009a).

Among many factors, the guidelines give washwater discharge criteria. It requires that when the exhaust gas cleaning system is operating in ports, harbours, or estuaries, the washwater monitoring and recording should be continuous. The monitored and recorded values should include pH, Polycyclic Aromatic Hydrocarbons (PAH), turbidity and temperature. Monitoring and equipment should also be operating continuously in other areas, except for short periods of maintenance and cleaning of equipment. Additionally, the discharge water has to comply with certain limits of pH, PAH, turbidity, and nitrates (IMO 2009a).

The data recording and processing device should be of robust, tamper-proof design with read-only capability. In addition, it should be capable of preparing reports over specified time periods, and data should be saved for a period of minimum 18 months. pH, oil content (i.e. PAH levels), and turbidity should be continuously monitored and recorded according to these recommendations. The International Maritime Organization states that the monitoring equipment should also meet the following performances (IMO 2009a):

- The pH electrode and pH meter should have a resolution of 0.1 pH units and temperature compensation
- The PAH monitoring equipment should be capable of monitoring PAH in water in a range of at least twice the given limited discharge concentration. The equipment should be demonstrated to operate correctly and not to deviate more than 5% in washwater with turbidity within the working range of the application

Ultraviolet light monitoring technology or equivalent should be used for applications discharging at lower flow rates and higher PAH concentrations, because of its reliable operating range (IMO 2009a).

Previous studies in the field of scrubber systems have been focused on installation feasibility on existing ships and new vessels (The Glosten Associates 2011) (ABS 2013), and if the scrubber technology is cost beneficial compared to other technologies such as fuel switch and LNG (The Glosten Associates 2011)

1.2 Objective

The objective of this thesis is to perform a Formal Safety Assessment (FSA) on an exhaust gas cleaning system manufactured by Wärtsilä. The results of the analysis will be evaluated and discussed prior to existing guidelines on exhaust gas cleaning systems, MEPC.184(59), published by the International Maritime Organization (IMO). Most importantly, the analysis will give awareness on issues regarding risk and safety on this new technology in the maritime industry.

1.3 Structure

First, the problem description of the master thesis is elaborated in Chapter 2. Chapter 3 covers descriptions of various methodologies: risk analysis techniques and the contents of the Formal Safety Assessment. Chapter 4 contains a system description of the open loop system manufactured by Wärtsilä, and background information of the handbook *Offshore Reliability Data* (OREDA) and software CARA-FaultTree v4.1. On the grounds of these chapters, Chapter 5 treat the execution of the Formal Safety Assessment. Discussions of both execution and results are given in Chapter 6, while the concluding remarks are elaborated in Chapter 7. Finally, further work is presented in Chapter 8.

1.4 LIMITATIONS

System description in Chapter 4 is limited by lacking information on the open loop system manufactured by Wärtsilä, which also limits the execution of the Formal Safety Assessment in Chapter 5. The analysis is based on a preliminary version of a P&ID, and additional information such as previous failure modes and failure rates would be preferable to gain greater perspective on the system. Additionally, the costs of risk control options are roughly estimated in the cost-benefit assessment, which results in an incorrect analysis. The main drawback of the study is that there are not found any previous Formal Safety Assessments of open loop systems, which sets limitations on the discussion of the results in Chapter 6. As a result, it is challenging to determine whether the results are credible or not.

2 Problem Description

Exhaust gas cleaning systems, also known as scrubbers, involve novel technologies that are unfamiliar to many in the industry, which result in uncertainty and mixed opinions on whether the technology is an adequate solution to reach the regulations on sulphur oxides (SO_x) emissions (DNV GL 2015a). Failures occurring in the early phases of the operation are often linked to manufacture or installation issues, so if a scrubber system is not functioning as it is designed, the ship might not meet the strict emission criteria of sulphur oxides (SO_x).

This master thesis is a continuation on a project thesis written the autumn of 2014. The thesis involved studying the background of emissions with an emphasis on sulphur oxides, given regulations from the Internation Maritime Organization (IMO) and descriptions of exhaust gas cleaning system designs. Finally, Technology Qualification Process by DNV GL was elaborated, together with a qualification process of an open loop system from Wärtsilä, which resulted in a FMECA and a risk matrix.

The objective with this master thesis is to further explore quantitatively what challenges the open loop system manufactured by Wärtsilä has in regards to system risks and safety. The study is executed by adopting a quantitative risk assessment method, Formal Safety Assessment (FSA), which consists of five steps. The FMECA and the risk matrix from the project thesis are the basis in Step 1 of the FSA. Furthermore, the FSA method is used to explore and locate the critical parameters and their effects of the given open loop system, together with discussing these results prior to the existing guidelines.

3 METHODOLOGY

This chapter covers the descriptions of the various methodologies subsequently used in this thesis. First, risk analysis techniques such as FMECA, event trees and Risk Contribution Trees (RCT) are presented, followed by an explanation of the approaches in Formal Safety Assessment (FSA).

3.1 RISK ANALYSIS TECHNIQUES

3.1.1 FMECA

Failure mode, Effect and Criticality Analysis (FMECA) is an inductive process to determine equipment functions, functional failure modes, and assessing the causes of such failures and their effects/consequences. In addition, the effect on production availability and reliability, safety, cost, quality, etc. on a component level is covered (Kristiansen 2005). For each component, every failure mode and its resulting effects on the rest of the system are submitted into a specific FMECA worksheet (Rausand 2011).

The main advantages with FMECA are that it is widely used and easy to perform. It is systematic and comprehensive, and should be able to locate all failure modes with an electrical or mechanical basis. Besides, it is suitable for complex systems, while being flexible so that the level of detail can be adapted to the objectives of the analysis. A limitation is that its benefits are dependant on the experience of the analyst and requires a hierarchical system drawing as a basis for the analysis. Additionally, it does only consider hazards arising from single-point failures and does not identify hazards caused by combinations of failures, and it can be both time-consuming and expensive (Rausand 2011).

The technique of conducting a FMECA can be examined in two levels. Failure Mode and Effects Analysis (FMEA) is the first level. It identifies potential failure modes of the components or sub-systems, and the effects on system performance by identifying the potential severity of the effect. Secondly, a Criticality Analysis is utilised to rank the items under investigation. Together, these two levels provide information for making risk management decisions (Pillay and Wang 2003).

The analysis should be performed iteratively in all stages of design and operation of a system, and can be performed both qualitatively and quantitatively. Therefore, in addition to other criteria such as level of information, the process can be conducted in several ways. The objectives are (Rausand 2011):

a) Identify how each of the system components can conceivably fail (i.e. what are the failure modes?)
b) Determine the causes of these failure modes
c) Identify the effects that each failure mode can have on the rest of the system
d) Describe how the failure modes can be detected
e) Determine the frequency of each failure mode occurring
f) Determine the severity of the various failure modes are
g) Assess the risk related to each failure mode
h) Identify risk-mitigating actions/features that may be relevant

The first step is to organize the information of the system (i.e. system concept, design and operational requirements). By breaking down the system into functions, subsystems, and components, a system model can be created. Hence, a rational, repeatable, and systematic approach to analyse the system can be completed. Block diagrams and fault tree diagrams (ref. Section 3.1.2) are additional techniques used for describing the relations between the components/functions (Pillay and Wang 2003).

The second step is to describe the possible failures and failure modes. DNV defines a failure as loss of the ability of an item to perform the required (specified) function within the limits set for its intended use, which occurs when the margin to failure is negative. Thus, a failure mode is the observed manner of failure on a specific manner (DNV 2013a). Failure modes are dependent on the specific system, component, and operating environment, and are sometimes described as categories of failures. Examples of failure modes are: collapse, seized, sag, buckled, etc. (Pillay and Wang 2003).

Further, the causes of the failure modes are covered. For instance, the causes could be outcomes from physical or chemical processes, design effects, quality defects, etc., which are reasons for failure. Typical causes are: incorrect material used, poor weld, corrosion, error in dimension, bad maintenance, etc. Please note, more than one failure cause can result in a failure mode, and all potential causes of failures, including human errors, should be identified (Pillay and Wang 2003).

Probability of each failure mode of an item can be obtained from a reliable source to determine how often each failure mode will occur. Table 3.1 shows an example on classification of probability by frequency. It is common to let the frequency in one category be approximately ten times higher than in the preceding category, which gives a logarithmic scale (Rausand 2011).

Table 3.1: Probability classes (Rausand 2011)

Category	Frequency (per year)	Description
5 Fairly normal	10-1	Event that is expected to occur frequently.
4 Occasional	1-0.1	Event that happens now and then, will normally be experienced by the personnel.
3 Possible	10^{-1}-10^{-3}	Rare event, but will possibly be experienced by the personnel.
2 Remote	10^{-3}-10^{-5}	Very rare event that will not necessarily be experienced in any similar plant.
1 Improbable	0-10^{-5}	Extremely rare event.

The consequences of the failure mode can be classified into different levels according to their impacts. Table 3.2 presents an example of such a classification, and lists common categories on consequences. The consequences are often ranked that the severity of a category is around ten times higher than the severity of the preceding category (Rausand 2011).

Table 3.2: Classification of consequences according to their severity (Rausand 2011)

	Consequence types		
	People	Environment	Property
5. Catastrophic	Several fatalities	Time for restitution of ecological resources ≥ 5 years	Total loss of system and major damage outside system area
4. Severe loss	One fatality	Time for restitution of ecological resources = 2-5 years	Loss of main part of system; production interrupted for months
3. Major damage	Permanent disability, prolonged hospital treatment	Time for restitution of ecological resources ≤ 2 years	Considerable system damage; production interrupted for weeks
2. Damage	Medical treatment and lost-time injury	Local environmental damage of short duration (≤ 1 month)	Minor system damage; minor production influence
1. Minor damage	Minor injury, annoyance, disturbance	Minor environmental damage	Minor property damage

Likewise, the criticality number of the item under a severity class may be quantitatively calculated as follows (Pillay and Wang 2003):

$$C = \sum_{i=1}^{N} E_i L_i t \tag{3.1}$$

where:

E_i: Failure consequence probability of failure mode i. (i.e. the probability that the possible effects will occur, given that failure mode i has taken place).

L_i: Occurrence likelihood of failure mode i.

N: Number of the failure modes of the item, which fall under a particular severity classification.

t: Duration of applicable mission phase.

To facilitate the ranking and validation of ranking, consequence and probability indices are recommended to be on a logarithmic scale. Hence, a risk index may be established and further used to create a risk matrix (IMO 2002).

$$\text{Risk} = \text{Probability} \times \text{Consequence} \tag{3.2}$$

$$\text{Log (Risk)} = \log\text{ (Probability)} \times \log\text{ (Consequence)} \tag{3.3}$$

3.1.2 Fault Tree Analysis

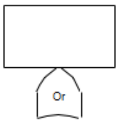
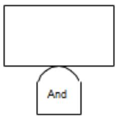
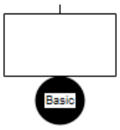
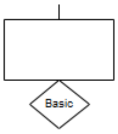
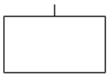
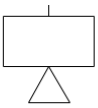
Fault tree analysis (FTA) is a commonly used method for causal analysis of hazardous events, and has been utilised in various application areas. The ideas behind FTA are (Pillay and Wang 2003):

1. A failure in a system can trigger other consequent failures
2. A problem might be traced backwards to its root causes

A FMECA encompasses all parts or functions of a component or system, while FTA is applied selectively to the most severe failure effects. It complements FMECA by starting with a top-level failure effect and tracks the failure to potential causes by creating a tree structure (Hecht 2004). The technique aims to detect how multiple lower level events can combine to produce an undesirable top-level effect, and is therefore an important component of reliability analysis, and safety programs (Rausand 2011).

Table 3.3 shows the most commonly adopted fault tree symbols. A FTA starts with a specified system failure or an accident as a top event. Immediate causal events (i.e. A_1, A_2), which may lead to the top event, are identified and connected to the top event through a logic gate (i.e. OR-gate or AND-gate). Further, potential causal events (i.e. $A_{i,1}$, $A_{i,2}$) that may lead to event A_i are identified and connected to event A_i through a logic gate. This procedure continues deductively until a suitable level of detail is reached by repeatedly asking ¨What are the reasons for this event?¨. Note, basic events are the events on the lowest level in the constructed tree (Rausand and Høyland 2004).

Table 3.3: Fault tree symbols (Rausand 2011)

Symbol		Description
OR-gate		The OR-gate indicates that the output event A occurs if any of the input events E_i occur.
AND-gate		The AND-gate indicates that the output event A occurs only when all the input events E_i occur at the same time.
Basic event		The basic event represents a basic equipment failure that requires no further development of failure causes.
Undeveloped event		The undeveloped event represents an event that is not examined further because information is unavailable or because its consequence is insignificant.
Comment rectangle		The comment rectangle is for supplementary information.
Transfer-out		The transfer-out symbol indicates that the fault tree is developed further at the occurrence of the corresponding transfer-in symbol.
Transfer-in		

According to *System Reliability Theory* by Rausand and Høyland, a FTA is executed in five steps (Rausand and Høyland 2004):

1. Definition of the problem and the boundary conditions
2. Construction of the fault tree
3. Identification of minimal cut and/or path sets
4. Qualitative analysis of the fault tree
5. Quantitative analysis of the fault tree

Definition of the problem considers that each top event should always give answer to the following questions (Rausand and Høyland 2004):

- What: Describes what type of critical event (accident) is occurring (e.g. explosion).
- Where: Describes where the critical event occurs (e.g. boiler).
- When: Describes when the critical event occurs (e.g. during normal operation).

It is important to define the boundary conditions in order to get a consistent analysis. The physical boundaries of the system are the parts of the system that should be included in the analysis and which parts that should not. When deciding the initial conditions, questions such as the following should be answered: What is the operational state of the system when the top event is occurring? Is the system running on full/reduced capacity? Which valves are open/closed? Which pumps are functioning? Besides, boundary conditions with respect to external stresses should be considered (e.g. earthquake, lightning, sabotage). Finally, the level of resolution should be evaluated: How far down in detail should the potential reasons for a failed state be identified? For instance, is it sufficient to define a reason to be a valve failure, or should the failure be further descriptive, such as valve housing, valve stem, and so on. Note that this is often confined due to the accuracy of the available information (Rausand and Høyland 2004).

3.1.2.1 Identification of Minimal Cut and Path Sets

A cut set in a fault tree is the combination of fault events that will result in the top event. In other words, a cut set is a set of basic events that occur at the same time and ensure that the top event occurs. A cut set is minimal if the set cannot be reduced without loosing its status as a cut set. It is considered feasible to identify the minimal sets by inspection without any large procedure or algorithm. However, large and complex fault trees need an efficient algorithm, as the algorithm MOCUS (method for obtaining cut sets) (Rausand and Høyland 2004).

3.1.2.2 MOCUS

MOCUS is an efficient algorithm that can be adopted to find the minimal cut and path sets in a fault tree. The simplest way to explain MOCUS is to demonstrate it with an example of a fault tree where gates are numbered from G0 to G6 and with eight basic events (ref. Figure 3.1). The approach is extracted from *User's manual for CARA-FaultTree v4.1* (Sydvest Software 2000).

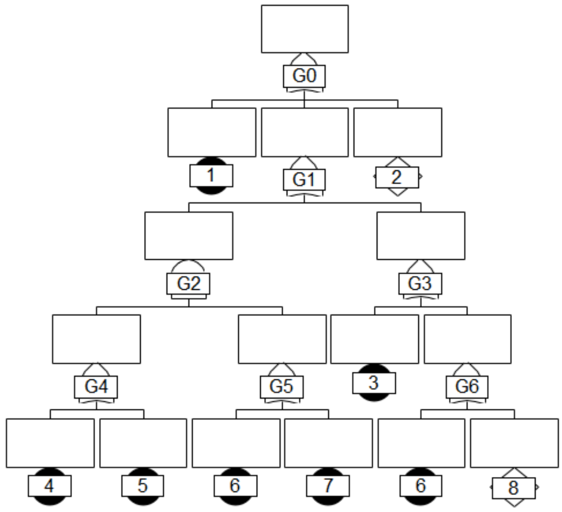


Figure 3.1: Fault tree MOCUS (Sydvest Software 2000)

The algorithm starts at the top event G0. This is an OR-gate and the writing starts:

1
G1
2

If the G0 was an AND-gate, the inputs should have been written as the first row in a matrix:

1, G1, 2

Then, each of the three inputs (1, G1 and 2) will cause the TOP event to occur and each of them will form a cut set.

The idea behind MOCUS is to gradually replace each gate with its inputs (i.e. basic events, new gates). This continues until one has gone through the whole fault tree and is left with basic events. Hence, the rows in the resulting matrix represent the cut sets in the fault tree.

Since G1 is an OR-gate and the next step is to write:

1
G2
G3
2

Because G2 is an AND-gate we get:

1
G4, G5
G3
2

And since G3 is and OR-gate:

1
G4, G5
3
G6
2

Since G4 is an OR-gate:

1
4, G5

5, G5
3
G6
2

Because G5 is an OR-gate

1
4,6
4,7
5,6
5,7
3
G6
2

Finally, since G6 us an OR-gate, we get:

1
4,6
4,7
5,6
5,7
3
6
8
2

The result is the following 9 cut sets:

[1], [2], [3], [6], [8], [4,6], [4,7], [5,6] and [5,7]

Since [6] is a cut set, the cut sets [4,6] and [5,6] are not minimal, and we have the following minimal cut sets:

[1], [2], [3], [6], [8], [4,7] and [5,7]

The reason why this algorithm leads to non-minimal cut sets is a result of basic event 6 occurring several places in the fault tree.

To find the minimal path sets, one starts with the so-called dual fault tree. It can be obtained by replacing all the AND-gates in the original tree (ref. Figure 3.1) with OR-gates and conversely. Additionally, the events in the dual fault tree should be complements to the corresponding events in the original fault tree.

3.1.2.3 Qualitative Fault Tree Evaluation

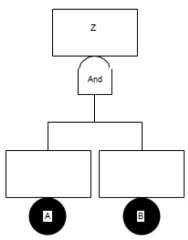
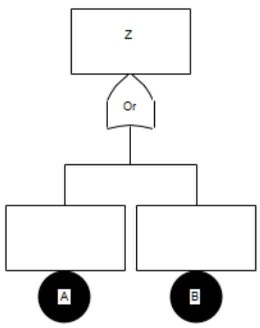
As FMECA, fault tree analysis can be executed both qualitatively and quantitatively of complex systems (Hecht 2004). A qualitative fault tree evaluation determines the minimal cut sets and common cause failures. An evaluation can be carried out on the basis of the minimal cut sets. The evaluation can be performed by looking at the criticality of a cut set, which is dependant on the number of basic events in the cut set. Normally, a cut set of order 1 is considered to be more critical than a cut set of order 2, or more. Having a cut set of order 1 means that the top event will occur as soon as the corresponding basic event occurs. Furthermore, when there is a cut set with two basis events, both of the basic events have to happen simultaneously to cause the top event to occur. Additionally, the types of basic events of a minimal cut set have to be ranked. For instance, the criticality of the various cut sets can be ranked after the following ranked basic events (Rausand and Høyland 2004):

1. Human error
2. Active equipment failure
3. Passive equipment failure

3.1.2.4 Quantitative Fault Tree Evaluation

In a fault tree, which contains independent basic events (i.e. appears only once in the tree structure), the top event probability can be obtained by working the basic event probabilities up through the tree. The gate event probabilities are calculated starting at the base of the tree and climbing upwards until the top event probability is obtained. However, this method is not appropriate if the tree has repeated events. The minimal cut-set method is a more appropriate method to find the occurrence probability of a top event. Two mini-trees in Table 3.4 illustrate how the occurrence can be obtained (Pillay and Wang 2003).

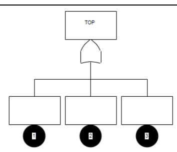
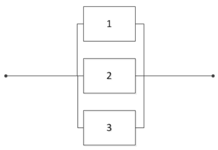
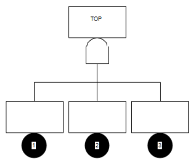
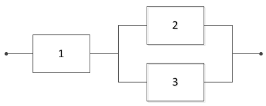
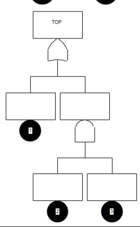
Table 3.4: Minimum cut set (Pillay and Wang 2003)

Fault tree	Quantitative Fault Tree Evaluation
	The minimum cut set for the minimal tree on the left is A·B If one event is independent from the other, the occurrence probability of top event Z is: $P(Z) = P(A \cdot B) = P(A) \times P(B)$ where P(A) and P(B) are the occurrence probabilities of events A and B
	The minimum cut set for the mini-tree on the left is A+B. If one event is independent from the other, the occurrence of the probability of top event Z is: $P(Z) = P(A + B)$ $= P(A) + P(B) - P(A \cdot B)$ $= P(A) + P(B) - P(A) \times P(B)$ where P(A) and P(B) are the occurrence probabilities of events A and B.

3.1.2.5 RELIABILITY BLOCK DIAGRAMS VERSUS FAULT TREES

It is possible to convert a fault tree to a reliability block diagram and vice versa. Table 3.5 displays the relationship between simple reliability block diagrams and fault trees. A connection through a block in a reliability block diagram illustrates that the component represented by the block is functioning, and none specified failure modes of the component are occurring. The same failure modes for a component are represented in a failure tree through basic events.

Table 3.5: Reliability block diagrams versus fault trees (Rausand and Høyland 2004)

Reliability Block Diagram	Fault Tree
	
	
	

3.1.3 EVENT TREE ANALYSIS

Event tree analysis is a common inductive method, which has been used since the early 1970s and is utilised within various application areas. The method is suitable for quantitative analysis and is, in a combination with fault trees, usable to analyse barrier failures. It is also possible to perform it qualitatively, since the event tree is dependant on the objectives of the analysis and the available relevant data (Rausand 2011).

As the fault tree analysis, event tree analysis is a graphical and probabilistic method, and is a suitable method to modulate and analyse accident scenarios. The difference between the two methods is that the fault tree analysis is used to study the causes of a hazardous event, while the event tree analysis is employed to study the possible accident scenarios following the same event. Event trees have a forward logic, and the result of a tree is a diagram displaying the possible accident scenarios, also referred to as event sequences, which may follow a specified hazardous event. Additionally, external events that influence the accident scenario might be combined with the event tree (Rausand 2011).

When executing an event tree analysis, it is important that the analyst has sufficient system knowledge and understanding, as well as a logical and creative mind-set. The analysis estimates the consequence probabilities based on a given initiating event. Hence, the first step is to define the initiating event, together with identifying applicable safety systems, mechanisms, situations, quantifiable success, and failure states for each event. Safety systems, mechanisms and situation characteristics, which function as barriers in the consequence development process, are established in chronological order. Then, the probabilities of the outcomes of each pivotal event (i.e. an event can only have two different outcomes) are estimated and an initial event tree is established. The probability of a pivotal event is independent of the previous events. Two events are independent if one event does not give us any information about whether or not another event will occur. Hence, the events have no influence on each other, which is not necessarily the exact situation in real life (Kristiansen 2005).

3.1.4 RISK CONTRIBUTION TREE

A Risk Contribution Tree (RCT) is a combination of fault tree and event tree analyses, and displays diagrammatically the distribution of risk among different accident categories and sub-categories (IMO 2002). An example of a RCT model is to be found in Appendix B. The structure below the accident category is a graphical representation of the accident sub-categories, which is similar to a fault tree with its use of logical symbols. Additionally, it shows the combinations of contributory factors relevant to each sub-category. Hence, the term ¨Contribution Fault Tree¨ has been used. The structures above the accident category level are the event trees (Pillay and Wang 2003).

Incorporating historical data in the Risk Contribution Tree quantifies it, and if no data is available expert judgement is regarded as an appropriate alternative. According to the International Maritime Organization, there are three steps to quantify the RCT (IMO 2002):

1. Categories and sub-categories of accidents are quantified in terms of the frequency of accidents
2. The severity of accident outcomes are quantified in terms of magnitude and consequence
3. The risk of the categories and sub-categories of accidents can be expressed as F-N curves or potential loss of lives (PLL) based on the frequency of accidents and the severity of the outcome of the accidents. Thus, the distribution of risks across all the

sub-categories of accidents is determined in risk terms, so as to display which categories contribute to risk

3.1.5 CONSEQUENCE SPECTRUM

A consequence spectrum, also known as a risk picture or a risk profile, is related to a hazardous event. Most likely, a hazardous event leads to several potential consequences. Let consequences be C_n, from i into a finite number n of discrete consequences. The probability, p_i, of a potential consequence, C_i, depends on the physical situation and if barriers are functioning or not. Figure 3.2 illustrates consequences and probabilities related to a hazardous event. The consequence spectrum can also be presented in a table (Rausand 2011).

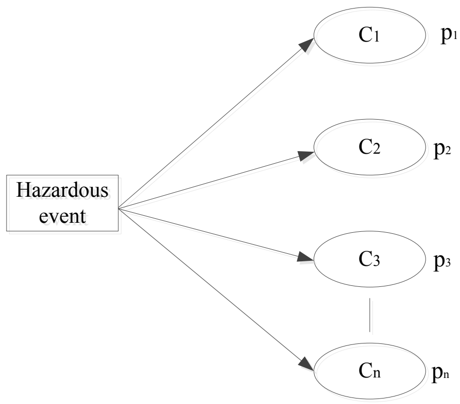


Figure 3.2: Consequence spectrum for a hazardous event (Rausand 2011)

3.2 FORMAL SAFETY ASSESSMENT

3.2.1 INTRODUCTION

Formal Safety Assessment (FSA) is a new approach in the maritime industry, and can be utilised as a tool to help evaluate new regulations or to compare proposed changes with existing standards (IMO 2015). It uses standard techniques of risk and cost-benefit assessment to assist in the decision making process (Pillay and Wang 2003). According to *Technology and Safety of Marine Systems* by A. Pillay and J. Wang, the FSA may (Pillay and Wang 2003):

1. Improve the performance of the current fleet, be able to measure performance change, and ensure that new ships are good designs
2. Ensure the experience from the field is used in the current fleet and that any lessons learned are incorporated into new ships

3. Provide a mechanism for predicting and controlling the most likely scenarios that could result in incidents

Formal Safety Assessment consists of five steps aimed at improving maritime safety, which includes protection of life, health, the maritime environment and property (IMO 2002) :

1. Identification of hazards
2. Risk analysis
3. Risk control options (RCO)
4. Cost-benefit assessment
5. Recommendations for decision-making

These five steps are elaborated in the following sections, mostly according to IMO and *Maritime Transportation* by Svein Kristiansen. The Maritime Safety Committee (MSC) and the Maritime Environment Protection Committee (MEPC) approved Guidelines for Formal Safety Assessment (FSA) for use in the IMO rule-making process in April 2002 (IMO 2002). Formal Safety Assessment is also frequently employed in the process of improving and developing classification rules. Furthermore, it has also been applied to the safety assessment of individual ships (Kristiansen 2005).

However, the interactions are in reality not as simple as following the five steps. Figure 3.3 illustrates the flow chart of the methodology. There are repeated iterations, which makes the process effective as it constantly checks itself for changes along the analysis. Results and findings from one step are often used as feedback and input to several other steps, which makes the methodology quite complex (Kristiansen 2005).

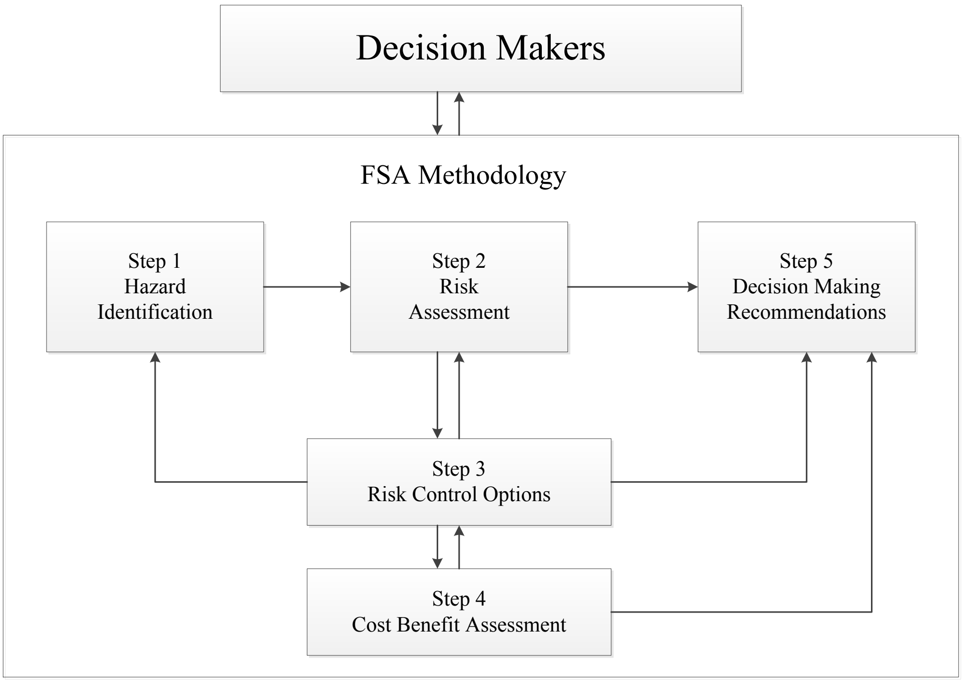


Figure 3.3: Flow chart of the Formal Safety Assessment methodology (IMO 2002)

3.2.2 STEP 1: HAZARD IDENTIFICATION

Hazard identification is the first step of the Formal Safety Assessment approach. The aim with this step is to identify relevant hazards (i.e. undesirable accidental outcomes), which could affect the ship operation under consideration (Kristiansen 2005). The list of hazards and associated scenarios should be prioritized by risk level specific to the problem under review (IMO 2002).

3.2.2.1 3.2.2.1 APPROACH

According to *Maritime Transportation* by Svein Kristiansen, Step 1 consists of three minor stages:

- Problem definition
- Hazard identification
- Hazard screening

The first stage is to make a precise and carefully defined problem definition, which is important to express the objective of the Formal Safety Assessment. It would include a description of the system/activities, and their relation to the rules and regulations. Furthermore, identifying the boundary of the analysis is crucial (Kristiansen 2005).

Stage two, hazard identification, generally adapts combinations of both creative and analytical techniques. Generic accident outcomes (i.e. consequences), causes and influencing factors are outlined and used in one or several techniques. Collision, fire, explosion, hull, and machinery failure are examples of generic accident outcomes, while causes could for instance be related to human causes, structural causes, mechanical causes, etc. Influencing factors could be categorised such as the likelihood of underlying causes occurring, likelihood of an underlying cause progressing to a major accident outcome and etc. The generic elements may be found by applying brainstorming strategies to identify relevant hazards (Kristiansen 2005).

The hazard screening stage is the third and final stage. It involves structuring the findings in the previous stage. Risk matrix is a common adopted technique, where the hazards are plotted in a matrix as a function of the severity of the consequences and the probability of occurrence. However, assessing risk (i.e. severity, probability) of the hazards should also be implemented in the second of the five steps in the Formal Safety Assessment. It is difficult to assess and find a clear boundary between these two steps, but in order to be loyal to the definitions of hazard and risk, the construction of techniques such as risk matrix should also be included in the second step in the approach (Kristiansen 2005).

3.2.3 Step 2: Risk Assessment

The purpose of the risk assessment is to investigate the causes and consequences of the more important scenarios identified in Step 1, in detail. This can be achieved by adopting suitable risk techniques (IMO 2002). A frequently used method is the Risk Contribution Tree (RCT), which is elaborated in Section 3.1.4. The method being adopted should address different types of risk, which depends on the problem under consideration. Common types of risks are risks to people, the environment or property (Kristiansen 2005).

3.2.3.1 Approach

Generally, Step 2 is divided into a qualitative and a quantitative risk assessment. According to *Maritime Transportation*, Step 2 may be illustrated as a sequence of four stages (Kristiansen 2005):

- Structure logical relationships
- Structure and quantify influence diagrams
- Quantify contribution trees
- Calculate total risk of loss of life, pollution, and damage to property

The qualitative risk assessment involves stage one and two, while the quantitative analysis is the two following stages. It is important to include a quantitative analysis to gain a accurate understanding of the estimates given to see the effects of risk control options/measures through the cost-benefit analysis in Step 4 (Kristiansen 2005).

3.2.3.2 Qualitative Risk Assessment

The two first stages structure logical relationships, and structure and quantify influence diagrams. Fault tree analysis is a frequently used method to structure logical relationships underlying an accident, where knowledge and experiences with the system being analysed is important (ref. Section 3.1.2). Risk profile is another common approach, which is often utilised for the qualitative risk analysis. It is a simplified fault tree with no logical gates between the underlying causes. Moreover, risk profiles are deducted from historical accidents rather than from underlying causes/failures as in fault trees (Kristiansen 2005).

Influence diagrams in stage two illustrate factors that influence the risks in a system or activity. Regulatory influences, corporate policy influences, organisational influences, and operational influences are examples on considerations within a diagram. Some factors influence the system performance directly (e.g. organizational policies, implementation), while others are more underlying influences. Influence diagrams can be constructed qualitatively or they can be quantified by assessing significance or importance of each influence. Quantified influence diagrams could be a useful basis for assessing the effectiveness of the safety measures or risk control options in Step 3 of the Formal Safety Assessment (Kristiansen 2005).

3.2.3.3 Quantitative Risk Assessment

It is significant to quantify both the absolute risk level and the relative importance of different causes to be able to find the high-risk areas. The quantitative risk assessment consists of the two remaining stages (i.e. quantify contribution trees, calculate total risk of life, pollution, and damage to property). These stages establish the relative and absolute importance of the underlying causes and the influencing causes of the system being analysed. It involves several risk estimates, such as F-N curves, PLL (Potential Loss of Life), and AIR (Average Individual Risk). The quantifications are based on historical data and expert judgement techniques. Commonly, historical data are broken down to a number of relevant accidents to find the likelihood of occurrence for the underlying causes. Quantification is performed in two directions in risk contribution tree, fault trees and event trees. It is essential that the potential consequences reflect factors such as injuries to people, and damages to environment and physical assets. Again, in order to get a valid analysis, considerable knowledge of the system is necessary (Kristiansen 2005).

The risk is estimated in the final stage. It is calculated by combining/multiplying the probabilities of occurrence with the severity of the consequences. The total risk picture is established if the risks for all possible outcomes of an accident category are calculated. The total risk picture should be presented numerically and graphically, with aid from the methods as mentioned above (i.e. F-N curves, etc.). However, the appropriate methods depend upon on the system under consideration (Kristiansen 2005).

3.2.4 STEP 3: RISK CONTROL OPTIONS (RCOs)

The aim with Step 3, also known as risk management, is to propose effective and practical risk control options (RCOs) (IMO 2002). The step is based on information found in Step 1 and Step 2, and the objective is to focus on the activities/systems with high risks or other concerns. It involves considering new safety measures and investigating to what degree current risk management and regulations reduce the system hazards (Kristiansen 2005).

3.2.4.1 APPROACH

According to the International Maritime Organization, Step 3 comprises the following four stages focusing on risk needing control, identifying potential risk control measures (RCMs), evaluating the effectives of the RCMs in reducing risk by re-evaluating Step 2, and grouping RCMs into practical regulatory options (IMO 2002).

On the other hand, *Maritime Transportation* claims that Step 3 involves three minor stages (Kristiansen 2005):

- Focus on risk areas needing control
- Identify potential risk control measures
- Group risk control measures into practical regulatory options

To determine the areas needing control, the following main aspects are assessed (IMO 2002, Kristiansen 2005):

1. Risk levels: Frequency of occurrence and severity of outcomes should be considered. Accidents with an unacceptable risk level become the primary focus. Risk control options must be implemented in order to make unacceptable risks, which are deemed acceptable, and ALARP.
2. Probability: Areas of the risk model with the highest probability of occurrence should be identified, and should be addressed regardless of the severity of the outcome. Even though a hazard scenario has a tolerable risk level with low severity and a high probability, it can be considered to be unacceptable from an operational point of view. A qualitative risk assessment could identify such situations.
3. Severity: The areas of the risk model that contribute to the highest severity outcomes should be identified, and also be addressed regardless of their probability.
4. Confidence: Areas where the risk model has considerable uncertainty either in risk, severity or probability should be identified and these uncertain areas should be further addressed.

New risk control measures (RCMs) are identified by structure review techniques, which may encourage the development of suitable measures and include risk attributes and causal chains. A risk attribute relates to how a measure might control a risk, while causal chains relate to where risk control should be introduced. Risk control measures have many different attributes. The International Maritime Organization divide the attributes of risk control measures into three categories: category A, B, and C (IMO 2002). The purpose of including attributes is to enable a structured thought process to understand how a risk control measure works (ref. Table 3.6). Many risks are result of complex chains of many events and causes. Hence, developing chains, as shown below, could assist the identification of difficult risk control measures (IMO 2002):

$$causal\ factors \rightarrow failure \rightarrow circumstances \rightarrow accident \rightarrow consequences$$

Table 3.6: Attributes of risk control measures (IMO 2002)

Category	Attributes of risk control measures
A	Preventive risk control, mitigating risk control
B	Engineering risk control, inherent risk control, procedural risk control
C	Diverse risk control, redundant risk control, passive risk control, independent risk control, dependent risk control, involved human factors, critical human factor

The International Maritime Organization claims that risk control measures should generally be aimed at one or more of the following (IMO 2002):

1. Reducing the frequency of failures through better design, procedures, organizational polices, training etc.
2. Mitigating the effect of failures, in order to prevent accidents
3. Alleviating the circumstances in which failures may occur
4. Mitigating the consequences of accidents

Based on the identified potential risk control options, a wide range of measures that reflect different areas, effects and characteristics should be grouped into practical regulatory options and forwarded to Step 4. There is a range of possible approaches. It is useful to group the risks control options in categories on the basis of practical type of regulatory options that could be implemented. In addition, it is practical to group the options/measures based on their effects on the considered system/activity (Kristiansen 2005).

3.2.5 STEP 4: COST-BENEFIT ANALYSIS

The objective of Step 4 is to identify and analyse the costs and benefits when applying the risk control options defined in Step 3 (IMO 2002).

3.2.5.1 APPROACH

Maritime Transportation claims that Step 4 is a series of five stages (Kristiansen 2005):

- Problem definition
- Identify costs and benefits
- Quantify costs and benefits
- Adaptation onto a common scale
- Evaluation uncertainty

The first stage is to make a problem definition based on the two previous steps and additional boundaries used explicitly in the cost-benefit assessment (CBA). Geographical and baseline year are examples of additional boundaries (Kristiansen 2005).

In the second stage costs and benefits related to each risk control options/measures are identified. Additionally, it is equally important to identify potential negative effects implemented risk control options could have on the system. For instance, implementations could cause reduced speed of the vessel, longer loading/unloading times, more downtime due to inspections and controls, etc. Costs should express the life cycle costs and may include following costs (Kristiansen 2005):

- Capital/investment cost
- Downtime or delay cost
- Training
- Labour costs
- Installation and commissioning cost
- Inspections, certification and auditing
- Maintenance

Benefits of adopting a risk control option/measure on a ship could include one or more of the following factors (Kristiansen 2005):

- Reduced number of injuries and fatalities
- Reduced casualties with vessel, including damage to and loss of cargo and damage to infrastructure (e.g. berths)
- Reduced environmental damage, including clean-up costs and impact on associated industries such as recreation and fisheries
- Increased availability of assets
- Reduction in costs related to search, rescue and salvage
- Reduced cost of insurance

The third stage is to quantify the identified relevant costs and benefits by using various methods and techniques. One approach is to evaluate the effect of the consequences on production factors. For instance, if a passenger or worker gets injured, length of hospitalisation, the degree of permanent disability, and the lost earnings are factors affecting costs of the injury. Overall, valuation approaches commonly result in a monetary cost of factors such as a fatality, pollution to the environment, etc. (Kristiansen 2005).

In the fourth stage, various risk control measures are adopted to a common scale to select the most cost-effective measures. There are several ways to perform a cost-benefit analysis of risk control/reduction measures. Generally, the Implied Cost of Averting a Fatality (ICAF) approach is employed in Formal Safety Assessments (FSAs). It estimates the achieved risk reduction in terms of cost utilising the following equation (Kristiansen 2005):

$$ICAF = \frac{Net\ annual\ cost\ of\ measure}{Reduction\ in\ annual\ fatality\ rate} \tag{3.4}$$

Gross Cost of Averting a Fatality (Gross CAF) and Net Cost of Averting a Fatality (NetCAF) are two other indices, and their definitions are (IMO 2002):

$$Gross\ CAF = \frac{\Delta C}{\Delta R} \tag{3.5}$$

$$Net\ CAF = \frac{\Delta C - \Delta B}{\Delta R} \tag{3.6}$$

ΔC is the cost per ship of the risk control option, while ΔB is the economic benefit per ship resulting from the implementation of the risk options. ΔR is the risk reduction per ship, in terms of the number of fatalities averted, implied by the risk control option. Approaches based on other factors than fatalities could also be employed. For instance, approaches based on damage to and affect on property and environment may be used for a cost-benefit assessment (IMO 2002).

The uncertainties involved in a cost-benefit analysis are evaluated in the final stage of Step 4. There are several different approaches for achieving this purpose. For instance, one method is to perform a sensitivity analysis of the parameters in the cost-benefit analysis and add the uncertainty of the parameter information implemented (Kristiansen 2005).

3.2.6 STEP 5: RECOMMENDATIONS FOR DECISION-MAKING

The purpose with Step 5 is to propose recommendations to the relevant decision makers. Recommended risk control options are based on the information generated in the previous steps in the Formal Safety Assessment. Generally, the results obtained in the cost-benefit analysis, in Step 4, form the basis of the proposed recommendations. It is especially important to evaluate the risk control options relative to each other using the common scale from Step 4 (Kristiansen 2005). According to the International Maritime Organization, the output from Step 5 includes (IMO 2002):

- An objective comparison of alternative options, based on the potential reduction of risks and cost effectiveness, in areas where legislation or rules should be reviewed or developed
- Feedback information to review the results generated in the previous step

4 MODELLING AND ANALYSIS

This chapter covers a system description of an open loop system from Wärtsilä, information about and behind *Offshore Reliability Data* (OREDA), and a description of software CARA-Fault Tree v4.1. First and foremost, the analysis in this thesis is based on a preliminary P&ID (120237-50000-001, rev.00) of the open loop system (ref. Appendix C).

4.1 SYSTEM DESCRIPTION

The scrubber system is an open loop system manufactured by Wärtsilä, who claims (Wärtsilä 2014c):

> *Wärtsilä exhaust gas cleaning technology is an economical and environmentally friendly solution for tackling all new and existing rules and regulations. The systems are suitable for both new builds and the retrofitting of existing vessels having either 2-stroke or 4-stroke engines, as well as for oil-fired boilers.*

An open loop system is water based, using the natural buffering capacity of seawater to remove SO_x. The scrubbers from Wärtsilä are designed to operate continuously, at full-specified exhaust gas flow. Characteristically, they are dimensioned for 100% exhaust gas capacity of the connected machinery. Table 4.1 lists the typical design specifications for operation, together with operating modes that are not permitted. The information is adapted from *Wärtsilä Scrubber Product Guide* (Wärtsilä 2014).

Table 4.1: Specifications and operation modes not permitted for open loop system (Wärtsilä 2014)

Design Specification for Operation	Operation Modes not Permitted
• Any fuel Sulphur content of up to 3.50% • Any machinery load up to design maximum load • Exhaust gas cleaned to a level where exhaust gas SOx-emission is not exceeding an equivalent of fuel Sulphur content 0.10% • Continuous operation • Operation in by-pass mode	• Consumption of fuel with Sulphur level exceeding 3.50%, without prior agreement with Wärtsilä • Exceeding maximum design load of the connected machinery, or limits stated in the Exhaust Gas Declaration • Prolonged dry running of the scrubber

Overall, the system consists of 15 different components of a total of 90 units: check valve, control valve, drainpipe, droplet separator, hydrocyclone, injection nozzle, manual gate valve, monitor, packed bed, pump, residence tank, scrubber device, sludge tank, steam cleaning, and venturi. The components/functions in the open loop scrubber system are classified into main and sub-components, based on the P&ID. The main components are: monitoring system, scrubbing water supply pump inlet, scrubber system, water treatment system, scrubbing water supply pump outlet, and water outlet. An identical P&ID with fixed component IDs is given in Appendix D. A symbol description and the sub-components are listed in Appendix E and F, respectively. The bypass arrangement, tank air vent, and blower connected to the residence tank are not evaluated and included in this research.

A schematic block diagram of the system is created in Microsoft's software Visio. This is done to gain a clear understanding on how the main components and their sub-components are physically connected. The structure is attached in G, which illustrates the process from inlet of seawater (Component ID 2.1) to discharge (Component ID 6.2) of washwater.

A manual gate valve feeds the system with seawater, together with a monitoring system and the water supply pumps. There are five parallels of water supply pumps installed to make sure large amounts of seawater reach the scrubber device. Manual gate valves are installed on both sides of each pump in order to perform maintenance or stop the supply of liquid if a pump experiences a failure.

The scrubber device/unit is the most essential component, which can be installed in either the engine casing or the funnel. It depends on the available space or other requirements of the client downstream of other components (e.g. silencers and economizers in the exhaust gas system). Its dimensions mainly vary on the exhaust gas mass flow and the requirement to limit the gas velocity within the scrubber device to 3 to 3.5m/s. Lower velocity provides that the scrubbing water drops out of the scrubbed gas flow and not to be carried away with the gas flow. The device is manufactured in high grade alloy steel to resist corrosion, and is therefore designed to be suitable for the life time of the ship (Wärtsilä 2014).

There are installed three injection nozzles, one steam cleaning, one droplet separator and two packed beds/wet filters inside the scrubber device, while the venturi has two injection nozzles fitted. Control valves are installed on three water supply pipelines, from the water supply pumps to the injection nozzles in the scrubber device and the venturi. Frequently, one or several venturis are connected to the lower part of the scrubber device. Moreover, seawater is injected into the venturi through injection nozzles to pre-conditioning the hot exhaust gas, before it is fed into the scrubber device (Wärtsilä 2014). The venturi creates a turbulent mixture of the hot exhaust and scrubbing water, reducing the exhaust gas temperature, SO_x, and PM. It also creates a small motion to limit pressure lost in the exhaust ducting from its way from the machinery (Wärtsilä 2014c). Scrubbing water is injected counter current to the exhaust gas inside the scrubber device, and is sprayed to both upper and lower sections. Packed beds improve the mixing of exhaust gas and water, and increase the surface area available for the SO_x scrubbing (Wärtsilä 2014c). Subsequently, all the washwater is drained through the bottom of the scrubber and led to a residence tank and the water treatment system. Then, the washwater is processed and the quality is monitored before the water is released to the sea (Wärtsilä 2014, {A/S, 2015 #144, Wärtsilä Moss A/S 2015).

The washwater is led to a residence tank, where the effluent is further lead to hydrocyclones. There are four hydrocyclones in parallel, where each parallel is supplied with a pump and two manual gate valves. The cleaned water is led back to the clean side of the residence tank, while sludge is fed to a sludge tank. The sludge production depends on fuel oil quality, and the composition of the sludge is mainly water, hydrocarbons, soot and metals. Since the sludge is stored onboard, the amount of water should be minimal, without losing the ability to pump the mixture (Wärtsilä 2014). Residual water in the sludge tank is pumped back to the residence tank. This pumping system consists of a pump with a manual gate valve on each side and a check valve (Wärtsilä 2014c).

Water supply pumps are placed in a parallel of three, which feed the cleaned washwater out of the residence tank. There are installed manual gate valves on both sides of each pump. Further, the water is monitored by the monitoring system with an outlet monitor and four manual gate valves. The water outlet is supplied by a check valve and control valve to discharge the water overboard.

4.1.1 MONITORING SYSTEM

The monitoring system is unlike the other monitoring systems onboard; it has new aspects and challenges associated with measuring pH, PAH, turbidity and temperatures. Commonly, both pH and temperature are measured in other monitoring systems onboard. According to DNV GL, the challenges are associated with measures of PAH and turbidity (Océane Balland). The monitoring units at inlet and outlet are installed with several manual gate valves, which are proven components onboard a vessel. Overall, the system is assumed to have a limited knowledgeable application area and a limited field history, regarding the degree of novelty of the system.

4.1.2 SCRUBBING WATER SUPPLY PUMP INLET

The scrubbing water supply pump inlet system has a redundancy of five parallels of pumps. According to American Bureau of Shipping, pumping systems in open loop systems require significant amounts of electrical power. An open loop system with an engine with 40 MW is estimated to have scrubbing water flow at 1,800 m^3 per hour and a pump electric load at 560 kW. It is assumed that the total electric load of a scrubber system is about 115 to 125 percentage of the scrubber pumps electric load. There are three main reasons why the system needs significant amounts of electric power (ABS 2013):

- Raising the water up from the lower engine room to the scrubber device
- Overcoming pressure losses in the piping
- Supply water at the required pressure to the spray nozzles (about 2 bar)

It is assumed that three out of five pumps have to be working in order to achieve the desired level of capacity. Each of the five pumps has a manual gate valves on each side. This is to be able to perform maintenance and/or to stop the supply of seawater if a pump has a failure. Additionally, each parallel has a check valve that allows seawater to flow through it in only one direction. Hence, no seawater is flowing back after leaving a parallel. The system ends with a manual valve, which can turn of the feeding of seawater to the scrubber system, if necessary.

4.1.3 SCRUBBER SYSTEM

The scrubber system, consisting of the scrubber device, venturi and their additional components, has several novel technologies and the application area is considered to have limited knowledge. A control valve is a proven technology, but they are now placed along pipelines controlling large amounts of seawater to the scrubber device and venturi. The scrubber device and the venturi are both known technologies from the land-based industry, but are still novel technologies onboard vessels. In addition, they include sub-components such as injection nozzles, steam cleaning, droplet separator, packed beds and drainpipe, which makes the whole system complex.

4.1.4 WATER TREATMENT SYSTEM

The water treatment system consists of three large components: residence tank, hydrocyclones, and sludge tank with additional sub-components. Wärtsilä often uses sludge tanks made of plastic with a size of approximately one cubic meter (Wärtsilä Hamworthy 2013). There are several tanks onboard a vessel. Though the tanks are placed in an application area with limited knowledge, the residence tank and sludge tank are not considered to be novel technologies. The hydrocyclones were developed in the 1950s (Hsieh and Rajamani 1986). They separate particles from the washwater, and they are extremely vital in order to meet the discharge boundaries of pH, PAH, turbidity, and temperature. There are four parallels of hydrocyclones, where each parallel has a pump with a manual gate valve on each side to feed the hydrocyclone with effluent. Additionally, there are two outlets: one with a manual gate valve and check valve, and the second has a control valve. It is assumed that three out of four pumps have to be working to achieve the desired level of capacity.

4.1.5 SCRUBBING WATER SUPPLY PUMP OUTLET

The scrubbing water supply pump outlet is a common arrangement with three parallels. Each parallel has manual gate valves on each side of a pump. It is assumed that two out of three pumps have to be working in order to achieve the desired level of capacity.

4.1.6 WATER OUTLET

The check valve and control valve in the water outlet are proven technologies, as the other pumps in the open loop system.

4.2 DATA COLLECTION

4.2.1 OREDA

The handbook *Offshore Reliability Data* (OREDA) is the basis of the data collection in this master thesis. It is published by the following OREDA participants: BP Exploration Operating Company Ltd, ConocoPhillips Skandinavia AS, Eni S.p.A Exploration & Production Division, ExxonMobil Production Company, Gassco (associated member), Shell Global Solutions UK, Statoil ASA and Total S.A. It is a project organisation sponsored by these oil and gas companies, and its purpose is to collect and exchange reliability data among the participating companies and to be used as a reliability data collection within the industry (SINTEF 2009).
OREDA has published five reliability and maintenance data handbooks, including the 2009 edition which is employed in this analysis. The current version has been prepared by SINTEF and is marketed by Det Norske Veritas (DNV). Moreover, the 2009 edition is split in two volumes, one for topside equipment and one for subsea equipment (SINTEF 2009). The composed data in this analysis is found collecting data from the topside volume.

Note that failures initiated by humans are implicitly included in the failure rate estimates. Hence, human errors are not evaluated to any further extent (SINTEF 2009).

4.2.1.1 FAILURE RATE

Failure rate function, often referenced as hazard rate or force mortality, expresses how likely it is that an item that has survived up to time t will fail during the next period of time. E.g., a woman who has reached the age of 95 years will have a higher probability of dying during the next year than a 20 year old woman. Hence, the failure rate function is usually a function of the time or the age of the item (SINTEF 2009).

Mathematically, the failure rate function is expressed with the time to failure (T) of the item (i.e. the time from the item is put into operation until the first failure occurs). Generally, it is difficult to predict the exact value of the time to failure, which makes T a random variable with an associated distribution. The failure rate function, z(t), is defined (SINTEF 2009):

$$z(t) = \lim_{\Delta t \to 0} \frac{1}{\Delta t} P(t < T \leq t + \Delta t | T > t) \quad (4.1)$$

This implies the approximation:

$$z(t) \cdot \Delta t \approx P(t < T \leq t + \Delta t | T > t) \quad (4.2)$$

The right hand side indicates the probability that the item will fail in the time interval when the item is still functioning at time t. Moreover, it means, the probability that an item that has reached the age t will fail within the next interval. The approximation therefore has the highest level of accuracy when Δt is the length of a significant short time interval (SINTEF 2009).

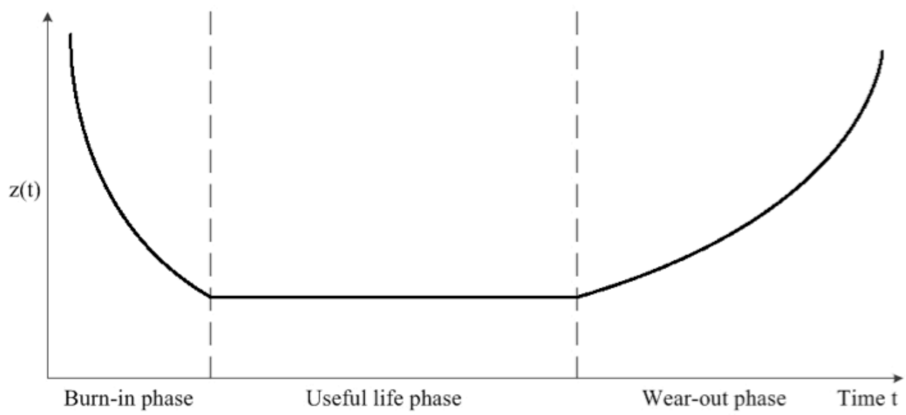


Figure 4.1: Bath-tube shape of failure rate (SINTEF 2009)

Figure 4.1 illustrates the bath-tube shape of the failure rate through various phases. The life of a technical item can be divided into three different phases: the burn-in, also known as early failure phase, the useful life phase, and the wear-out phase. The shape is often claimed to be a realistic model for mechanical equipment. Inherent quality problems in the item and/or installation problems are the reasons why the failure rate decreases in the burn-in phase. Installation problems have been neglected in the OREDA data collection. Therefore, the burn-in phase is not included in the OREDA database, and it is assumed that the data collection is started with the useful life phase. Additionally, many of the items in the data collection are subject to maintenance or replacement routines. Hence, the items are often replaced or refurbished before they reach the wear-out phase. Most importantly, generally the failure events in the database come from the useful life phase, where the failure rate is close to constant. Besides, an item is considered to be ¨as good as new¨ as long as it is functioning (SINTEF 2009).

This means, all the failure rate estimates in the handbook are based on the assumption that the failure rate function is constant and independent of time. This is defined mathematically $z(t)=\lambda$, i.e. the failure rates are exponential distributed with parameter λ (SINTEF 2009).

The mean time to failure (MTTF) is calculated based on the assumption of an estimated constant failure rate:

$$MTTF = \frac{1}{\lambda} \tag{4.3}$$

Descriptions on how OREDA finds estimators and confidence intervals for a homogeneous sample, and how these are found in multi-sample problems are clarified in the OREDA handbook.

4.2.1.2 Failure Modes

Table 4.2 lists the selected failure modes from the OREDA handbook. Failure modes are prearranged in combinations with maintainable items and failure mechanisms, respectively in the handbook.

Table 4.2: Failure modes (SINTEF 2009)

Failure Mode		Failure Mode	
ABO	Abnormal output	FTO	Fail to open on demand
AIR	Abnormal instrument reading	FTR	Fail to regulate
AOL	Abnormal output - Low	HIO	High output
DOP	Delayed operation	PLU	Plugged/Choked
ELP	External leakage - Process medium	SPO	Spurious operation
FTC	Fail to close on demand	STD	Structural deficiency
FTF	Fail to function on demand		

4.3 SOFTWARE

4.3.1 CARA-FAULTTREE V4.1

CARA-FaultTree v4.1 is a software used to construct and analyse fault trees. The construction involves building the fault tree by assembling logical gates and input events, and entering data such as identifiers, descriptive text and reliability data. Further, different analyses can be run by (e.g. calculations of mean time to failure (MTTF), unavailability, survival probability, measures of reliability importance and uncertainty analysis) (Sydvest Software 2000). Selected available system reliability measures are described in the following sections.

4.3.1.1 IDENTIFICATION OF MINIMAL CUT AND PATH SETS

As explained in Section 3.1.2, a cut set in a fault tree is a set of basic/input events that simultaneously occur and ensure that the top event occurs. According to *User's manual for CARA-FaultTree v4.1*, a path set is a set of basic events that do not occur simultaneously and ensure that the top event does not occur. CARA-FaultTree calculates the minimal cut and path sets by abstracting the algorithm MOCUS, as elaborated in Section 3.1.2 (Sydvest Software 2000).

4.3.1.2 THE PROBABILITY THAT THE TOP EVENT OCCURS AT TIME T

$Q_0(t)$ is the probability that the top event occurs at time t. If the state of each component is known at time t, then the state of the top event can be calculated regardless of what has happened up to time t. Thus, $Q_0(t)$ is exclusively determined by the $q_i(t)$'s. If one or several components in each minimal cut set have data of the category repairable unit or non-repairable unit, the corresponding $q_i(t)$'s will increase from $q_i(0) = 0$ to some asymptotic value $q_i(\infty) \leq 1$ implying $Q_0(t)$ to increase from $Q_0(t) = 0$ to $Q_0(t) \leq 1$ (Sydvest Software 2000).

4.3.1.3 THE PROBABILITY THAT THE TOP EVENT DOES NOT OCCUR IN [0,T) - R_0(T)

$R_0(t)$ is the probability that the top event does not occur in the time period from 0 to t. In other words, it is the probability that the system has survived up to time t. $R_0(t)$ does depend on what has happened up to time t, and not only the situation at time t. This is unlike $Q_0(t)$. Only when all components have failure data for the category non-repairable unit, we have $R_0(t) = 1 - Q_0(t)$ (Sydvest Software 2000).

4.3.1.4 *Mean Time to First System Failure - MTTF*

Mean time to the first system failure (MTTF) is the mean time to the first occurrence of the top event. It is always greater or equal to mean time between failures (MTBF), because all components are assumed to function at time t. However, this assumption cannot be made when the system has been restored after a system failure (Sydvest Software 2000).

4.3.1.5 *E(#failures)/Freq(TOP)/ Frequency Distribution*

The frequency of the top event is the expected number of occurrences of the top event in a period of time, for instance (Sydvest Software 2000):

Freq(TOP) = 2 occurrences per year (4.4)

Note the number of occurrences, e.g. X, is a random number in a given period of time. A topic of interest would be to obtain the distribution of X as well as the expected value of X, E(X). Then, the notation Freq(TOP) is not clear enough. The distribution of X is determined by the probabilities (i.e. P(X=0), P(X=1), P(X=2) etc.). Further, the expected value of X is given by (Sydvest Software 2000):

$$E(X) = \sum_{i=0}^{\infty} i \cdot P(X = i) \qquad (4.5)$$

When the times between consecutive occurrences of the top event are exponentially distributed, the number of failures X, in a unit period of time, will be Poisson distributed with parameter $\lambda = 1/E(X)$. The distribution of X is the following (Sydvest Software 2000):

$$P(X = i) = \frac{\lambda^i}{i!} e^{-\lambda} \qquad (4.6)$$

4.3.1.6 *Average System Availability in [0,t) - $A_{0,av}(t)$*

$A_{0,av}t$ is the fraction of time the system is available in the period from 0 to t. It will always be greater or equal to $1-Q_0(t)$, because the system is more available at time 0 than for a time greater than 0. Hence, the availability in the time period up to t, is greater than the availability at time t, $1-Q_0(t)$ (Sydvest Software 2000).

4.3.1.7 QUANTITATIVE RANKING OF MINIMAL CUT SETS

There are two ways to quantitatively rank minimal cut sets: cut set unavailability and cut set importance. Cut set availability quantifies the probability that a given cut set is in a failed state at time t. It is calculated as (Sydvest Software 2000):

$$Q_j = \prod_{i \in K_j} q_i(t) \tag{4.7}$$

where K_j denotes all components in the minimal cut set j.

Cut set importance is the conditional probability that minimal cut set j is failed at time t, given that the system is failed at time t. It is calculated as (Sydvest Software 2000):

$$I^{CI}(j) = \frac{Q_j}{Q_0(t)} \tag{4.8}$$

4.3.1.8 VESELY-FUSSELL`S MEASURE OF RELIABILITY IMPORTANCE

Vesely-Fussell's measure of reliability importance, $I^{VF}(i/t_0)$, is the probability that at least one minimal cut set with basic event i is failed at time t_0, given that the system fails at time t_0. CARA-FaultTree extracts the following approximation for a non-modularised tree:

$$I^{VF}(i/t_0) \approx \frac{\sum_{j=1}^{m_i} \check{Q}_j^i}{Q_0(t)} \tag{4.9}$$

The upper index i in $\check{Q}_j(t)$ tells that only the minimal cut sets containing basic event i are considered, $\check{Q}_j(t)$ is the probability that minimal cut set C_j fails at time t, and the number of minimal cut sets containing basic event i is denoted as m_i.

Notice that an improved version of this approximation is used in CARA-FaultTree for a modularised tree. Hence, the software can provide the importance measures for any basic event.

5 EXECUTION OF FORMAL SAFETY ASSESSMENT

In this chapter the execution of the Formal Safety Assessment of the open loop system manufactured by Wärtsilä is presented, together with the results along the analysis.

5.1 STEP 1: HAZARD IDENTIFICATION

As elaborated in Section 3.2.2, the aim of Step 1 is to identify the relevant hazards (i.e. undesirable accidental outcomes), which could affect the ship operation under consideration.

The objective of Step 1 is to identify potential risks and to understand what challenges the open loop system from Wärtsilä has in relation to system risks and safety, qualitatively. It is of importance to mention that this step was executed in the project thesis written autumn 2014, where a shorter version of DNV GL's Technology Qualification Process was performed. The analysis was carried out with help from OREDA, together with expert judgement by the author and Associate Professor Océane Balland. The results were a FMECA and a risk matrix, which are presented in the section below.

5.1.1 RESULTS

The FMECA is created in Microsoft software Excel and is documented in Appendix H. It consists of 153 cases, based on the 90 different components with different failure modes. Table 5.1 on the next page explains how the chosen columns in the FMECA are supplemented.

Table 5.1: Description of FMECA columns

FMECA Column	Description
FMECA ID	Each sub-component with a failure mode has a given FMECA ID
System	Every sub-component is categorised within a main system (ref. Appendix F)
Comments	Sub-components in parallel (hence redundancy) are commented
Component ID	Every sub-component has a component ID (ref. Appendix F)
Component	Type of component. E.g., manual gate valve, pump, packed bed, etc.
Component function	The purpose of the component in the open loop system
Failure mode	Failure mode
Failure cause	Failure cause
Local failure effect	The effect the failure has locally in the open loop system
Global failure effect	The effect the failure has globally in the open loop system
Failure detection	Tools or procedures to detect failure
Existing safeguard	Existing tools and procedures to prevent failure
Consequence	Consequence is estimated based on the previous columns
Probability	Probability is estimated based on the previous columns, experience data from OREDA and conversations with Associate Professor Balland
Criticality	Given by consequence and probability in risk matrix
Action items	A failure mode with criticality at M or H are given recommendations on new actions to become acceptable

A risk matrix is created in order to get an illustrative table to rank risk and focus qualification efforts where the benefits are the greatest. The matrix is represented in Figure 5.1. It is made based on the FMECA IDs with probability and consequences. The number in each cell represents the amount of IDs, which has the same probability and consequence combination.

			Probability				
			1	2	3	4	5
			Impossible	Remote	Possible	Occasional	Fairly normal
Consequence	5	Catastrophic	0	4	4	0	0
	4	Severe loss	0	9	6	0	0
	3	Major damage	0	28	46	4	0
	2	Damage	0	2	49	0	0
	1	Minor damage	0	0	1	0	0

Figure 5.1: Risk matrix (Mari Løvald Andresen 2014)

The qualitative method shows that on the basis of 153 FMECA IDs, 52% are ranked with a low risk, 45% with a medium risk, and 3% with a high risk. Additional tables of each risk group are to be found from Appendix I to Appendix K.

The results convey that the scrubber system, which has a share of 22% of the total of 153 FMECA IDs, generally has the highest risk within medium and high risk. The water treatment system is contrary, which has a share at 34%; it has a large share of failure modes with low risk and a smaller portion is categorised as medium risk. Scrubbing water supply pump inlet and scrubbing water supply pump outlet have a share of 16% and 8%, respectively. Both systems have failure modes categorised with low risk and have a smaller quantity of medium risk. The monitoring system has a share of 14% of the total 153 FMECA IDs, where the failure modes are almost equally categorised with low and medium risk. Water outlet consists of the fewest amounts of components and has a 6% share of the total failure modes, and it appears to have an almost even distribution in low and medium risk region. Overall, plugged/chocked, external leakage, fail to open on demand and fail to close on demand are the four commonly failure modes.

The water treatment system has a large share of components categorised with low risk. Table I.1 in Appendix I illustrates the large share is due to the valves within the open loop system (i.e. manual gate valves, check valve, control valves), aside from the pump and sludge tank. Scrubber water supply inlet, scrubber water supply outlet, and water outlet are also assumed to have valves with failure modes with low risks. Aside from the valves, inlet monitor and outlet monitor in the monitoring system are assumed to have low risk, in addition to pumps in scrubber water supply inlet and scrubber water supply outlet. External leakage has a share of 36% of the total amount of 80 FMECA ID’s with low risk, mostly due to the many valves distributed in the various systems. Fail to close, fail to open and plugged/choked are other frequent contributors appearing in valves. Pump is the second largest component with low risk, with external leakage as failure mode. Abnormal outputs and spurious operation are the assumed failure modes in the inlet monitor and outlet monitor. Table I.1 also shows there could be potential failures in drainpipe and injection nozzles, due to failure mode plugged/choked.

Table J.1 in Appendix J shows the distribution of components with medium risk. It shows the control valves 3.1, 3.2 and 3.3 are large contributors, which is due to failures such as fail to close, fail to control, fail to open and plugged/choked. Moreover, the inlet monitor, manual gate valve and outlet monitor in the monitoring system are assumed to have medium risk. These failure modes are categorised within the medium risk domain, because of fail to function in inlet monitor and outlet monitor and by fail to open in manual gate valve. Additionally, the large amount of failure modes with manual gate valves in the scrubbing water supply pump inlet is worth mentioning. Table J.1 shows that these valves are manual gate valves 2.1 and 2.22.

Only two components are assumed to have high risk. These are the drainpipe and injection nozzles in the scrubber system. Components 3.15, 3.5, 3.6 and 3.7 are presented as the determined components in Table K.1 in Appendix K. The table shows the components are categorised with high risk due to the failure cause plugged/choked.

5.2 STEP 2: RISK ASSESSMENT

As mentioned in Section 3.2.3, the purpose of the risk assessment in Step 2 is to extensively investigate the causes and consequences of the more important scenarios identified in Step 1.The cases with low risk are assumed to be below the ALARP region where the probability of occurrence is negligible. Hence, mainly the cases with medium and high risk will be further evaluated.

Risk Contribution Tree (RCT) is the selected analysis technique in Step 2, which is a combination of fault tree (FTA) and event tree (ETA) analyses (ref. Section 3.1.4). This analysis starts with modelling the fault trees, followed by modelling of the event tree. Both analyses are based on the most severe failure effects from the FMECA in Step 1 and the schematic block diagram in Appendix G.

5.2.1 ACCIDENT CATEGORIES

Each fault tree and event tree is categorised within an accident category. An accident category is a designation of accidents reported to their nature, such as grounding, collision, explosion, etc. (IMO 2002). The chosen accident categories in this analysis are Overpressure, Hazards related to loading/discharging operations, and Purification failure. The categories are established based on the FMECA in Step 1 and expert judgement by the author. Note that the second category, Hazards related to loading/discharging operations, regards accidents with loading and discharging operations on the open loop system itself and not the vessel.

5.2.2 FAULT TREE MODELLING

Each top event, also known as an accident sub category, is placed below one of the three accident categories in the risk contribution tree. Table 5.2 shows the distribution of six fault trees within the three accident categories. The assumptions made during the fault tree modelling in software CARA-FaultTree are presented subsequent to the table.

Table 5.2: Distribution of fault trees in accident categories

Accident Category	Fault Tree		Appendix
Overpressure	F1	Overpressure in scrubber device and venturi	M
Hazards related to loading/discharging operations	F2	No seawater to scrubber device and venturi	N
Purification failure	F3	Inlet monitor 1.1 does not measure pH, PAH, turbidity and temperature	O
	F4	Outlet monitor 1.4 does not measure pH, PAH, turbidity and temperature	P
	F5	Washwater not purified	Q
	F6	Exhaust gas not washed in scrubber device	R

Only technical failures are evaluated in the fault trees, and it is expected that the failures occur during normal operation. As mentioned in Section 4.2.1, many of the items covered in OREDA are subject to some maintenance or replacement policy, and the failure rate estimates are therefore based on an assumption that failure rates are constant and independent of time (SINTEF 2009). According to Tony Kråkenes at SINTEF, test intervals are irrelevant to OREDA, as it only collects failures (Tony Kråkenes). Hence, Repairable is the chosen failure data category for basic events in CARA-FaultTree.

The total number of failures divided by the total time in service, n/τ, found in OREDA, is set as the parameter λ/1E6 in Repairable in CARA-FaultTree. Active repair time (hours) in OREDA presents the mean and maximum calendar time (hours) that is required to repair and return the component to a state where it functions again (SINTEF 2009). The column Mean in OREDA is therefore set as the parameter MTTR in Repairable in CARA-FaultTree.

There are four severity class types to categorise failure modes in OREDA: critical failure, degraded failure, incipient failure and unknown. OREDA defines critical failure as a failure, which causes immediate and complete loss of an equipment unit's capability of providing its output. A degraded failure is a failure not regarded as critical, but it prevents an equipment unit from providing its output within specifications (SINTEF 2009). Failure modes with a critical failure are the prioritised when creating the fault trees. Moreover, Failure mechanisms given in OREDA, as mention in Section 4.2.1, are not included in the fault trees, due to the limited construction criteria in CARA-FaultTree and limited information about the open loop system.

CARA-FaultTree supports two methods for calculating unavailability, $Q_0(t)$, upper bound approximation and exact calculation (ERAC) (Sydvest Software 2000). Exact calculation is the preferred alternative in this analysis, since it is the most accurate method. Average availability is found by employing Monte Carlo (stochastic) simulation. Survival probability, $R_0(t)$, mean time to first failure, MTTF, and frequencies of top events are calculated using numerical integration. Additionally, Survival probability, $R_0(t)$, and failure frequency distribution are calculated by utilising Monte Carlo (stochastic) simulation. The frequency of top event (occurrence per hour) is found by hand calculation (upper bound approximation), numerical integration and Monte Carlo simulation.

Point of time and mission time in the employed analyses are set to be one year (8760 hours). The assumption is based on recommendation from PhD Candidate Christoph Thieme (Christoph Alexander Thieme). Each Monte Carlo simulation runs with 1000 simulations and the seed for simulation is set to be 10430.

The following subsections explain the construction of the six fault trees, which are modelled and simulated in software CARA-FaultTree (ref. Section 4.3.1). Hand calculations of the six top event probabilities are given in Appendix K.

5.2.2.1 F1: Overpressure in Scrubber Device and Venturi

It is assumed that overpressure in scrubber device and venturi could lead to an explosion. Fault tree number one, Overpressure in scrubber device and venturi, shows the potential threats that could lead to overpressure in the casings. It is constructed by the eight following immediate causal events:

- Manual valve gate 2.1 fails to close
- Inlet monitor system fails to function
- Overpressure created by failure in scrubbing water supply pump inlet
- Manual gate valve 2.22 fails to close
- Control valves in scrubber system fail to control seawater pressure or close
- Blockage inside scrubber device
- Drainpipe 3.15 blocked
- Exhaust outlet 3.16 blocked by impurities

Manual valve gate 2.1 and manual gate valve 2.22 in scrubbing water supply pump inlet are evaluated to fail to close by basic event 1 and basic event 2. If these valves do not close on demand, it is assumed the scrubber device and venturi could be overloaded by water pressure.

The inlet monitoring system could fail to function by failure to close manual gate valve 1.2 or manual gate valve 1.3 on demand (i.e. basic event 4 or basic event 5), or if the electronics and sensing element in inlet monitor 1.1 fails to function. The inlet monitor is assumed to be out of function if one of the failure modes, fail to function on demand (basic event 6) or spurious operation (basic event 7) is occurring.

Failures in three out of five parallels in the scrubbing water supply pump inlet are assumed to result in overpressure. One parallel could be down if one of two manual gate valves fails due to failure close on demand or if there is overpressure caused by the centrifugal pump. Further, it is expected that high output in centrifugal pump can cause overpressure.

The control valves in the scrubber system could fail if any two out of three valves fail to control seawater pressure or they fail to close on demand. A control valve is assumed to be failing by either the failure modes, failure to close on demand or by abnormal instrument readings.

Blockage inside the scrubber device is also assumed to cause overpressure in the scrubber device and venturi if steam cleaning, droplet separator and packed beds are blocked. Hence, from basic event 29 to basic event 32, plugged/choked are the assumed failure modes.

Drainpipe 3.15 blocked is the seventh immediate causal event. The drainpipe could be blocked if an injection nozzle falls down and covers the drain or if sludge blocks the drain inside of the scrubber device. Additionally, impurities are expected to potentially block exhaust outlet 3.16. It is estimated that basic event 3 has the same reliability data as the basic events in the immediate causal event, blockage inside scrubber device.

The utilised reliability data in fault tree one is displayed in the table below. Overall, the fault tree consists of 38 basic events, where 30 basic events are categorised within severity class critical. Manual gate valves have a large proportion (47%) of the total amount of basic events with critical severity. The eight residual events are categorised as degraded, which are abnormal instrument reading in control valves and plugged/chocked in droplet separator, exhaust outlet, packed beds and steam cleaning.

Table 5.3: Reliability data in fault tree, Overpressure in scrubber device and venturi (SINTEF 2009)

Component	Failure mode	Severity Class	λ/1E6	Error factor	MTTR	Error factor	Calendar time
Drainpipe	PLU	Critical	7.88	1	3.7	1	4.6937
Injection nozzle	Looseness	Critical	4.58	1	5.3	1	0.6545
Centrifugal pump	HIO	Critical	2.84	1	2	1	0.3526
Inlet monitor	FTF	Critical	1.76	1	3.3	1	3.3998
Inlet monitor	SPO	Critical	1.47	1	2.2	1	3.3998
Manual gate valve	FTC	Critical	1.21	1	3.8	1	22.29
Control valve	FTC	Critical	1.21	1	3.8	1	22.29
Exhaust outlet	PLU	Degraded	1.53	1	15	1	0.6545
Steam cleaning	PLU	Degraded	1.53	1	15	1	0.6545
Droplet separator	PLU	Degraded	1.53	1	15	1	0.6545
Packed bed	PLU	Degraded	1.53	1	15	1	0.6545
Packed bed	PLU	Degraded	1.53	1	15	1	0.6545
Control valve	AIR	Degraded	0.18	1	3.8	1	22.29

5.2.2.2 F2: No Seawater to Scrubber Device and Venturi

Fault tree number two, No seawater to scrubber device and venturi, illustrates a situation where no seawater is led to the scrubber system. It is the only fault tree within the second accident category, Hazards related to loading/discharging, and it is constructed by the five following immediate causal events:

- Manual gate valve 2.1 fails to open
- No seawater access scrubbing water supply pump inlet
- Scrubbing water supply pump inlet fails to function
- Manual gate valve 2.22 fails to open
- Injection nozzles fail to disperse water

Manual valve gate 2.1 and manual gate valve 2.22 in scrubbing water supply pump inlet are estimated to fail to open by basic event 1 and basic event 2. If these valves do not open on demand, no water will be pumped onboard and the scrubber system will not receive water, respectively.

The second immediate casual event is when no seawater enters the scrubbing water supply pump inlet. This can be caused if both the pipeline 2.23 is broken and the inlet monitor system fails to function. Basic event 3 expresses that the pipeline could get damaged due to external leakage with process medium. It is assumed that the inlet monitor system could fail to function because of failure to open manual gate valve 1.2 or manual gate valve 1.3 on demand (i.e. basic event 4, basic event 5), or if the electronics and sensing element in inlet monitor 1.1 fails to function. The inlet monitor is assumed to be down if two out of three failure modes are occurring: low abnormal output (basic event 6), fail to function on demand (basic event 7) and spurious operation (basic event 8).

Scrubbing water supply pump inlet fails to function if any three out of five parallels fail to deliver water to the scrubber system. A parallel fails if one of two manual gate valves fails to open or if a centrifugal pump fails to lift seawater to the scrubber system in the funnel. The check valves in all parallels are neglected.

The last immediate event is when all injection nozzles fail to disperse water, which is distributed further in three analogous events, connected with an OR-gate. Any of these three events occur if either the injection nozzles fail or if the control valve fails. An injection nozzle is assumed to fail if it is plugged/chocked or if it loosens from its position and falls down. While a control valve fails due to either failure to open on demand or abnormal instrument reading.

The utilised reliability data in the second fault tree is displayed in the Table 5.4. Overall, the fault tree consists of 54 basic events, where 46 of them are categorised within severity class critical. Again, the manual gate valves have a large share (30%). The eight residual events are categorised as degraded, which are abnormal instrument reading in control valves and plugged/chocked in injection nozzles.

Table 5.4: Reliability data in fault tree, No seawater to scrubber device and venturi(SINTEF 2009)

Component	Failure mode	Severity Class	λ/1E6	Error factor	MTTR	Error factor	Calendar time
Centrifugal pump	ELP	Critical	14.18	1	15	1	0.3526
Centrifugal pump	FTS	Critical	8.51	1	33	1	0.3526
Injection nozzle	Looseness	Critical	4.58	1	5.3	1	0.6545
Pipeline	ELP	Critical	3.54	1	8.3	1	7.9054
Centrifugal pump	UST	Critical	2.84	1	124	1	0.3526
Centrifugal pump	STD	Critical	2.84	1	15	1	0.3526
Inlet monitor	FTF	Critical	1.76	1	3.3	1	3.3998
Inlet monitor	SPO	Critical	1.47	1	2.2	1	3.3998
Manual gate valve	FTO	Critical	1.12	1	5.9	1	22.2900
Control valve	FTO	Critical	1.12	1	5.9	1	22.2900
Inlet monitor	AOL	Critical	0.29	1	4	1	3.3998
Injection nozzle	PLU	Degraded	1.53	1	15	1	0.6545
Control valve	AIR	Degraded	0.18	1	3.8	1	22.2900

5.2.2.3 F3: Inlet Monitor 1.1 does not Measure pH, PAH, Turbidity and Temperature

Fault tree number three, Inlet monitor 1.1 does not measure pH, PAH, turbidity, and temperature, shows situations which cause the inlet monitor to fail to measure the properties of the seawater. It is the first fault tree within accident category Purification failure, and it is modelled by the two following immediate causal events:

- Manual gate valve 2.1 is out of function
- Electronics and sensing element in inlet monitor 1.1 fails to function

The manual gate valve 2.1 could be down if the following failure modes occur: delayed operation (basic event 1), external leakage with process medium (basic event 2), fail to close on demand (basic event 3), fail to regulate (basic event 4), spurious operation (basic event 5), or structural deficiency (basic event 6).

As in the second fault tree, electronics and sensing element in inlet monitor 1.1 could fail to function. The inlet monitor is assumed to be out of function if two out of three failure modes are occurring: low abnormal output (basic event 7), fail to function on demand (basic event 8), and spurious operation (basic event 9).

The fault tree consists of nine basic events, all with critical severity class. Manual gate valves have 67% and inlet monitor have 33% share of the failure modes, respectively. The utilised reliability data in fault tree three is displayed in Table 5.5 below.

Table 5.5: Reliability data in fault tree, Inlet monitor doesn't measure pH, PAH, turbidity & temperature (SINTEF 2009)

Component	Failure mode	Severity Class	λ/1E6	Error factor	MTTR	Error factor	Calendar time
Inlet monitor	FTF	Critical	1.76	1	3.3	1	3.3998
Inlet monitor	SPO	Critical	1.47	1	2.2	1	3.3998
Manual gate valve	FTO	Critical	1.12	1	5.9	1	22.29
Manual gate valve	FTR	Critical	0.58	1	2.4	1	22.29
Inlet monitor	AOL	Critical	0.29	1	4	1	3.3998
Manual gate valve	ELP	Critical	0.18	1	32	1	22.29
Manual gate valve	DOP	Critical	0.13	1	3	1	22.29
Manual gate valve	STD	Critical	0.13	1	5	1	22.29
Manual gate valve	SPO	Critical	0.04	1	6	1	22.29

5.2.2.4 F4: Outlet Monitor 1.4 does not Measure pH, PAH, Turbidity and Temperature

Fault tree four, Outlet monitor 1.4 does not measure pH, PAH, turbidity and temperature, is the second fault tree within the accident category Purification failure. The tree shows events that could result in outlet monitor 1.4 fails to measure the properties of the seawater, and it has the two following immediate causal events:

- No washwater access outlet monitor 1.4
- Electronics and sensing element in outlet monitor 1.4 fails to function

No washwater access outlet monitor 1.4 if manual gate valve 1.8 and manual gate valve 1.7 are out of function. The valves could be failing as a result of delayed operation, external leakage with process medium, fail to open on demand, fail to regulate, spurious operation, or structural deficiency.

The electronics and sensing element in outlet monitor 1.4 could be down and result in that the outlet monitor does not measure the water properties. The outlet monitor is assumed to be out of function if two out of three failure modes are occurring, which are low abnormal output (basic event 1), fail to function on demand (basic event 2) and spurious operation (basic event 3).

The fault tree consists of 15 basic events and all fall within the severity class critical. As in the third fault tree, manual gate valves have a large share (80%) of the total potential failure modes. The remaining 20% are failure modes related to the outlet monitor 1.4. The utilised reliability data in fault tree four is displayed in the Table 5.6.

Table 5.6: Reliability data in fault tree, Outlet monitor 1.4 doesn't measure pH, PAH, turbidity & temperature (SINTEF 2009)

Component	Failure mode	Severity Class	λ/1E6	Error factor	MTTR	Error factor	Calendar time
Outlet monitor	FTF	Critical	1.76	1	3.3	1	3.3998
Outlet monitor	SPO	Critical	1.47	1	2.2	1	3.3998
Manual gate valve	FTO	Critical	1.12	1	5.9	1	22.29
Manual gate valve	FTR	Critical	0.58	1	2.4	1	22.29
Outlet monitor	AOL	Critical	0.29	1	4	1	3.3998
Manual gate valve	ELP	Critical	0.18	1	32	1	22.29
Manual gate valve	DOP	Critical	0.13	1	3	1	22.29
Manual gate valve	STD	Critical	0.13	1	5	1	22.29
Manual gate valve	SPO	Critical	0.04	1	6	1	22.29

5.2.2.5 F5: Washwater not Purified

Fault tree five, washwater not purified, maps the potential situations that could result in untreated discharged washwater. The tree is constructed by the five following immediate causal events:

- Electronics and sensing element in inlet monitor 1.1 fails to function
- Control valve 4.35 fails to control washwater
- Hydrocyclones do not remove residuals from washwater
- Electronics and sensing element in outlet monitor 1.4 fails to function
- Control valve 6.2 fails to control washwater

The inlet monitor 1.1 and outlet monitor 1.4 could fail to function if the electronics and sensing elements fail to function. The monitors are assumed to be down if all of the failure modes are occurring: low abnormal output (i.e. basic event 1, basic event 5), fail to function on demand (i.e. basic event 2, basic event 6) and spurious operation (i.e. basic event 3, basic event 7).

Control valve 4.35 and control valve 6.2 are assumed to fail controlling washwater if failure mode abnormal instrument reading occurs (i.e. basic event 4, basic event 8).

Hydrocyclones fail to remove residuals from washwater if two out of four parallels are down. A parallel consists of one control valve and one hydrocyclone. A control valve could fail due to abnormal instrument reading, while a hydrocyclone fails if either there is an external leakage with process medium, the instrument is plugged/choked, or if it has structural deficiency. The manual gate valves, check valves, and pumps in the parallels are neglected.

The utilised reliability data in fault tree five is displayed in Table 5.7. Overall, the fault tree has 10 basic events with severity class critical, together with 14 basic events with severity class degraded. The components with critical reliability data are hydrocyclones (i.e. external leakage with process medium), inlet monitor (i.e. low abnormal output, fail to function on demand, spurious operation), and outlet monitor (i.e. low abnormal output, fail to function on demand, spurious operation). It is assumed that the control valves with failure mode abnormal instrument reading, and hydrocyclones with issues regarding plugged/choked and structural deficiency have degraded reliability data.

Table 5.7: Reliability data in fault tree, Washwater not purified (SINTEF 2009)

Component	Failure mode	Severity Class	λ/1E6	Error factor	MTTR	Error factor	Calendar time
Hydrocyclone	ELP	Critical	7.89	1	1.7	1	0.3803
Inlet monitor	FTF	Critical	1.76	1	3.3	1	3.3998
Outlet monitor	FTF	Critical	1.76	1	3.3	1	3.3998
Inlet monitor	SPO	Critical	1.47	1	2.2	1	3.3998
Outlet monitor	SPO	Critical	1.47	1	2.2	1	3.3998
Inlet monitor	AOL	Critical	0.29	1	4	1	3.3998
Outlet monitor	AOL	Critical	0.29	1	4	1	3.3998
Hydrocyclone	PLU	Degraded	2.63	1	70	1	0.3803
Hydrocyclone	STD	Degraded	2.63	1	10	1	0.3803
Control valve	AIR	Degraded	0.18	1	3.8	1	22.29

5.2.2.6 F6: Exhaust Gas Not Washed in Scrubber Device

Fault tree number six, Exhaust gas not washed in scrubber device, illustrates the situation when no exhaust gas is washed in the scrubber system. It is constructed by the six following immediate causal events:

- Manual gate valve 2.1 fails to open
- No seawater access scrubbing water supply pump inlet
- Scrubbing water supply pump inlet fails to function
- Manual gate valve 2.22 fails to open
- Injection nozzles fail to disperse water
- Blockage inside scrubber device

Manual valve gate 2.1 and manual gate valve 2.22 in scrubbing water supply pump inlet are estimated to fail to open by basic event 1 and basic event 2. If these two valves do not open on demand, no water will be pumped onboard and the scrubber system will not receive water, respectively.

The second immediate casual event is when no seawater accesses the scrubbing water supply pump inlet. This can be caused if both the pipeline 2.23 is broken and inlet monitor system fails to function. Basic event 3 expresses that the pipeline could get damaged due to external leakage with process medium. It is assumed that the inlet monitor system could fail to function by failure to open manual gate valve 1.2 or manual gate valve 1.3 on demand (i.e. basic event 4, basic event 5), or if the electronics and sensing element in inlet monitor 1.1 fails to function. The inlet monitor is assumed to be down if two out of three failure modes are occurring: low abnormal output (i.e. basic event 6), fail to function on demand (i.e. basic event 7) and spurious operation (i.e. basic event 8).

Scrubbing water supply pump inlet fails to function if any three out of five parallels fail to distribute seawater to the scrubber system. A parallel fails if one of the two manual gate valves fails to open or a centrifugal pump fails to lift seawater upwards to the scrubber system. The check valve in each parallel is neglected.

The second to last immediate event is when all injection nozzles fail to disperse water, which is distributed further in three analogous events, connected with an OR-gate. One of these three events occurs if either injection nozzles fail or if the control valve fails. An injection nozzle is assumed to fail if it is plugged/chocked or it loosens from its position and falls down. While a control valve fails because of either failure to open on demand or abnormal instrument reading.

Blockage inside scrubber device is the final immediate event. It is assumed there could be blockage inside the scrubber device when all of the following components are failing: steam cleaning 3.8 (i.e. basic event 55), droplet separator 3.9 (i.e. basic event 56), packed bed 3.10 (i.e. basic event 57), and packed bed 3.11 (i.e. basic event 58).

The utilised reliability data in the sixth fault tree is displayed in Table 5.8. Overall, the tree consists of 58 basic events, where 46 basic events are categorised within severity class critical and 12 events are categorised as degraded. The components with critical reliability data are centrifugal pumps (43%), control valves (7%), injection nozzles (11%), inlet monitor (7%), manual gate valves (30%), and pipeline (2%). Components with severity class degraded are control valves (25%), droplet separator (8%), injection nozzles (42%), packed beds (17%), and steam cleaning (8%).

Table 5.8: Reliability data in fault tree, Exhaust gas not washed in scrubber device (SINTEF 2009)

Component	Failure mode	Severity Class	λ/1E6	Error factor	MTTR	Error factor	Calendar time
Centrifugal pump	ELP	Critical	14.18	1	15	1	0.3526
Centrifugal pump	FTS	Critical	8.51	1	33	1	0.3526
Injection nozzle	Looseness	Critical	4.58	1	5.3	1	0.6545
Pipeline	ELP	Critical	3.54	1	8.3	1	7.9054
Centrifugal pump	UST	Critical	2.84	1	124	1	0.3526
Centrifugal pump	STD	Critical	2.84	1	15	1	0.3526
Inlet monitor	FTF	Critical	1.76	1	3.3	1	3.3998
Inlet monitor	SPO	Critical	1.47	1	2.2	1	3.3998
Manual gate valve	FTO	Critical	1.12	1	5.9	1	22.29
Control valve	FTO	Critical	1.12	1	5.9	1	22.29
Inlet monitor	AOL	Critical	0.29	1	4	1	3.3998
Injection nozzle	PLU	Degraded	1.53	1	15	1	0.6545
Steam cleaning	PLU	Degraded	1.53	1	15	1	0.6545
Droplet separator	PLU	Degraded	1.53	1	15	1	0.6545
Packed bed	PLU	Degraded	1.53	1	15	1	0.6545
Packed bed	PLU	Degraded	1.53	1	15	1	0.6545
Control valve	AIR	Degraded	0.18	1	3.8	1	22.29

5.2.3 EVENT TREE MODELLING

The following sections describe the background and modelling of three event trees, where the accident categories are respectively the initiating events.

Barriers, also referred to as safety function or protection layers, are established based on academic literature, P&ID in Appendix D, and expert judgement by the author (Rausand and Høyland 2004). As there are no published accident information of scrubber accidents available, several assumptions are made through the quantitative analyses. For instance, external events are not considered. The outcome from each event tree has an end event description, a frequency, and a degree of material damage. The frequency of each specific accident scenario is obtained by multiplying the frequency of the hazardous event by the probabilities for each barrier event along the pathway to the end event (Rausand 2011). The scale of material damage is given in Table 5.9.

Table 5.9: Consequence category, event tree outcomes (Rausand 2011)

Consequence Category	Description
5. Catastrophic	Total loss of system and major damage outside system area
4. Severe loss	Loss of main part of system; production interrupted for months
3. Major damage	Considerable system damage; production interrupted for weeks
2. Damage	Minor system damage; minor production influence
1. Minor damage	Minor property damage

5.2.3.1 Overpressure

Fault tree one, Overpressure in scrubber device and venturi, is the only fault tree categorised within the accident category Overpressure. Hence, it is the initiating event of the event tree of this category. It is assumed that the event tree has six barriers distributed within three barrier categories to stop or reduce the consequences of overpressure in the scrubber system (ref. Table 5.10). The modelled event tree is attached in Appendix S.

Table 5.10: Barrier categories and barriers in event tree one, Overpressure

Barrier Category	Barrier	True	False
Leakage protection	High water level alarm does not work	0.001	0.999
	Automatic stop of the water supply does not work	0.01	0.99
	Leakage of washwater	0.40	0.60
Fire or explosion	Start a fire	0.60	0.40
Fire protection	Sprinkler does not work	0.01	0.99
	Fire alarm does not work	0.001	0.999

Normally, the scrubber device is placed in the funnel. If the scrubber system is arranged with an exhaust bypass for each engine or boiler, existing exhaust outlets at the funnel top have to be retained. Thus, each scrubber will need a separate exhaust pipe, which should be at least the same size as the existing exhaust pipe. If an integrated scrubber is fitted, which combines the exhaust from several engines and boilers, it is necessary with an exhaust pipe with a larger diameter. Therefore, at least one large new exhaust pipe, and maybe several new exhaust pipes have to be integrated in the funnel. If there is not enough space in the funnel or it cannot be expanded during retrofitting, additional pipes and scrubber device can be modulated aft or to one side of the funnel (ABS 2013). It is commented on the P&ID in Appendix D that exhaust stack bypass arrangement should be added for each scrubber unit. So, it can be assumed there are several additional outlets in the funnel in addition to the scrubber device itself. This means if there is overpressure in a casing and a fire or explosion occurs, it would make a large impact on several components, especially considering the fact that the washwater inside the scrubber device contains acid chlorides and is corrosive (ABS 2013).

The first barrier category, Leakage protection, concerns the potential for flooding from the scrubber device caused by overpressure. According to American Bureau of Shipping, there are concerns regarding flooding of the scrubber device, so therefore is a scrubber automation system installed to prevent flooding. It includes a high water level alarm, an automatic stop of the water supply to the scrubber, and opening of the exhaust bypass (ABS 2013). The bypass arrangement is neglected in this master thesis, as stated in Section 4.1. However, high water level alarm and the automatic stop of water supply to the scrubber are considered as highly relevant barriers. It is assumed that it is a 0.1% chance that the high water level alarm does not work, while the automatic stop of the water supply has a 1% chance of not working. The probabilities are estimated based on an article, published in 2007 regarding risk of LNG carrier operations (Vanem, Antão et al. 2008). Besides, in Leakage protection, it is assumed a leakage from the scrubber device might take place. The probability of a leakage is assumed to be relatively high (40%).

The fire or explosion scenario describes a potential accident where a fire occurs, caused by overpressure. It is assumed that either a fire starts inside the funnel and/or the machinery space or no fire is initiated. It is expected that it is a 60% chance for fire when an explosion occurs and a 40% chance a fire will not occur. The percentages are based on accident statistics from DNV, who claims two-thirds of all fires onboard ships start in the engine room, and the origins of fires in the engine rooms are: electrical 9%, hotwork 7%, component failure 14%, boiler incidents 14%, and oil leakage 56% (DNV 2000).

The same probabilities of high water level alarm and automatic stop of water supply in Leakage protection are utilised respectively for the fire alarm and the sprinkler system in the third barrier, Fire protection.

The following additional assumptions are made when creating the event tree of the accident category Overpressure:

- Unavailability of overpressure is obtained from the average availability of fault tree one, Overpressure in scrubber device and venturi
- If the high water level alarm works, subsequent unwanted scenarios are averted
- If the automatic stop of water supply is functioning, subsequent unwanted scenarios are averted
- Though there is leakage, it is expected that there is still a probability that a fire occurs
- If there is no fire, fire protection is not needed

5.2.3.2 HAZARDS RELATED TO LOADING/DISCHARGING OPERATIONS

The second fault tree, No seawater to scrubber device and venturi, is the only fault tree within accident category Hazards related to loading/discharging operations. Hence, it is the initiating event of the event tree of this category. The event tree is presumed to have six implemented barriers, distributed in two categories (ref. Table 5.11). The modelled event tree is attached in Appendix T.

Table 5.11: Barrier categories and barriers in event tree two, Hazards related to loading/discharging operations

Barrier Category	Barrier	True	False
Electrical power protection	Separate generator does not work	0.01	0.99
	Switchboard does not work	0.001	0.999
	Local starter does not work	0.01	0.99
Automation and control system does not work	Scrubber alarm does not work	0.001	0.999
	Control panel in engine room does not work	0.001	0.999

As elaborated in Section 4.1.2, pumping systems in open loop systems require significant amounts of electric power. Hence, Electrical power protection is selected as the first barrier category. It is assumed that a vessel could use a separate generator to supply the scrubber system with additional electric power if the hazardous event occurs. It is assumed that a separate generator has a 1% chance of not working. According to American Bureau of Shipping, retrofitting of a scrubber system requires additional electric power and modification of the main switchboard to provide feeder circuit breakers. Besides, one or more power distribution boards would be installed and local starters fitted close to the motors (ABS 2013). Hence, switchboard and local starters are also considered as implemented barriers in Electrical power protection. It is anticipated that the switchboard and the local starters have 0.1% and 1% chance of not working, respectively.

Automation and control system is set as the second category barrier. American Bureau of Shipping reports that control panels can be local to the scrubber, and basic scrubber control should be available from the engine control room as a connection between the scrubber alarms and the ship's central alarm and monitoring system (ABS 2013). Hence, these are considered as potential barriers for this barrier category, and it is presumed that both scrubber alarm and control panel have 0.1% chance of not working.

The following additional assumptions are made when creating the event tree of accident category Hazards related to loading/discharging operations:

- Unavailability of hazards related to loading/discharging is obtained from the average availability of fault tree two, No seawater to scrubber device and venturi
- If the separate generator works, the risk is averted

5.2.3.3 Purification Failure

Four fault trees are categorised within accident category Purification failure. The event tree of this accident category is presumed to have three implemented barriers, distributed in two categories (ref. Table 5.12). The created event tree is attached in Appendix U.

Table 5.12: Barrier categories and barriers in event tree three, Purification failure

Barrier Category	Barrier	True	False
Automation and control system	Scrubber alarm does not work	0.001	0.999
	Control panel in engine room does not work	0.001	0.999
Outlet monitoring protection	Outlet monitor 1.4 fails to measure pH, PAH, turbidity and temperature	0.01	0.99

As mentioned in Section 1.1.1, Regulation 4 in MARPOL Annex VI allows the use of an alternative compliance method at least as effective in terms of emission reductions as that required in MARPOL Annex VI, including standards in Regulation 14 (IMO 2009a). This means, the scrubber system has to work successfully to meet the requirements. In other words, failure with purification could potentially lead to an unserviceable system.

The first barrier category is Automation and control system. The scrubbing process starts inside the scrubber device, and it is therefore assumed to be the location of the first preventive events. As mentioned in the previous event tree, the scrubber system is assumed to contain scrubber alarms and a control panel connected to the engine room. Hence, these barriers are considered as relevant and the reliabilities of these barriers are the same as assumed in Table 5.11.

2009 guidelines for exhaust gas cleaning systems oblige that when the EGC system is operating in ports, harbours, or estuaries, and in other areas, the washwater monitoring and recording should be continuous. The values should include pH, PAH, turbidity and temperature. The only exception is in short periods of maintenance and cleaning of the equipment (IMO 2009a). Therefore, the second barrier category is expected to be Outlet monitoring protection. Outlet monitor 1.4 should measure pH pAH, turbidity, and temperature of the discharge water, and it is assumed the monitor has 1% chance of not working.

The following additional assumptions are made when creating the event tree of accident category Purification failure:

- Unavailability of hazards related to loading/discharging is obtained from the average availability of fault tree five, Washwater not purified, since it is the most critical fault tree in this accident category
- If the scrubber alarm works, the risk is averted

5.2.4 RISK ASSESSMENT RESULTS

The constructed risk contribution tree (RCT) is attached in Appendix V. The illustrations of fault tree number three and five are not included due to limited picture quality and margins. The two following sections present the results from the six fault trees and the three event trees.

5.2.4.1 FAULT TREE RESULTS

This section goes through the results from the top event calculations from software CARA-FaultTree, and hand calculations are presented in Appendix L.

Unavailability, $Q_0(t)$, is the probability that the TOP event occurs at time t (Sydvest Software 2000). Figure 5.2 illustrates the unavailability among the six fault trees developed in Section 5.2.2. The unavailability is found by employing exact calculation (ERAC). The x- and y-axis illustrate respectively the time in hours and the unavailability of the fault trees. The figure has the trend as elaborated in Section 4.3.1; the corresponding $q_i(t)$'s increases from $q_i(0)=0$ to asymptotic values $q_i(\infty) \leq 1$, since all of the basic events have data of the category repairable.

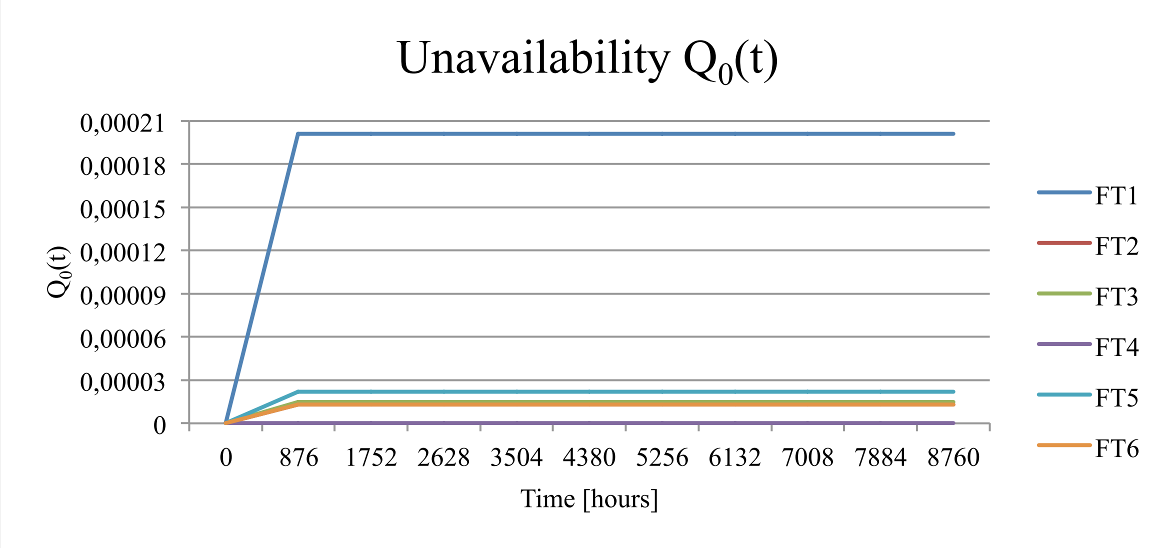


Figure 5.2: Unavailability of fault trees through one year

Table 5.13 lists the average availability of the fault trees through an entire year (8760 hours), which are found by employing *Monte Carlo simulation*. Table 5.14 lists the survival probabilities of the various fault trees by numerical integration: the expected number of failures during one year, expected number of failures per unit time, and the mean time to first system failure (MTTF).

Table 5.13: Average availability through one year calculated by Monte Carlo simulation

Fault Tree	Average Availability	Fault Tree	Average Availability
F1	0.999742	F4	1
F2	0.999994	F5	0.999971
F3	0.999996	F6	0.999972

Table 5.14: Survival probabilities of fault trees calculated by numerical integration

Fault Tree	Expected # of failures in period	Expected # of failures/unit time	MTTF
F1	0.35366000	4.04E-05	13163.2
F2	0.01962870	2.24E-06	18388.3
F3	0.01909670	2.18E-06	18398.7
F4	0.00000073	8.37E-11	18777.8
F5	0.06512820	7.43E-06	17526.0
F6	0.01962870	2.24E-06	18388.3

Figure 5.3 and Figure 5.4 illustrate the survival function, $R_0(t)$, calculated by *Monte Carlo simulation* and *numerical integration*, respectively. The time in hours is given at the x-axis and the survival function is presented at the y-axis.

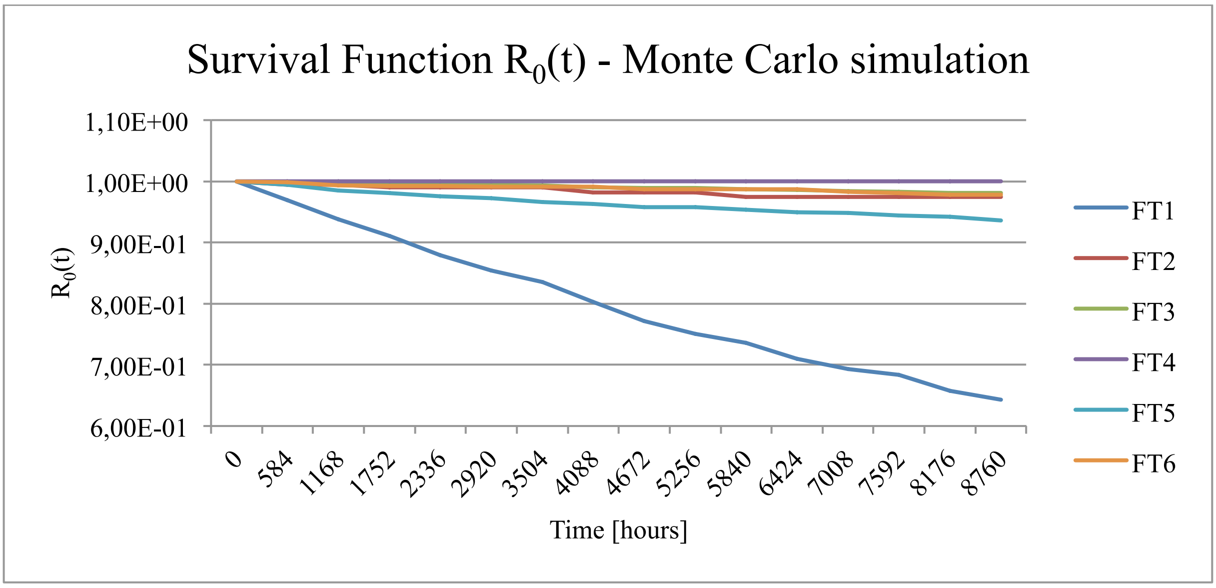


Figure 5.3: Survival function of fault trees calculated by Monte Carlo simulation

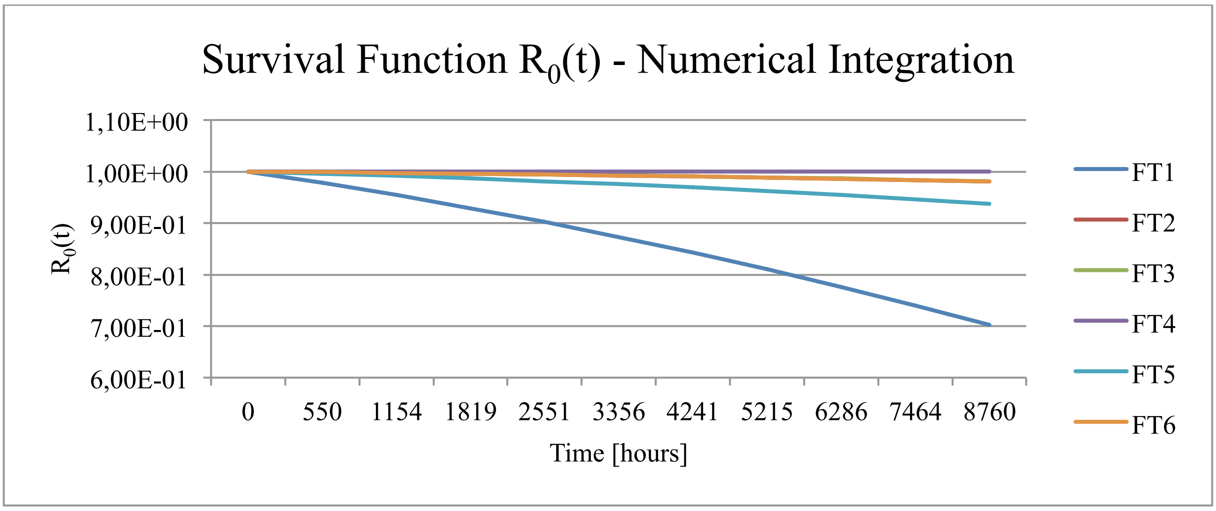


Figure 5.4: Survival function of fault trees calculated by numerical integration

Figure 5.5 displays the failure frequency distribution through one year, calculated by *Monte Carlo simulation*. The x-axis shows the number of times the top event fails, n, and the y-axis illustrates the frequency of the top event failure.

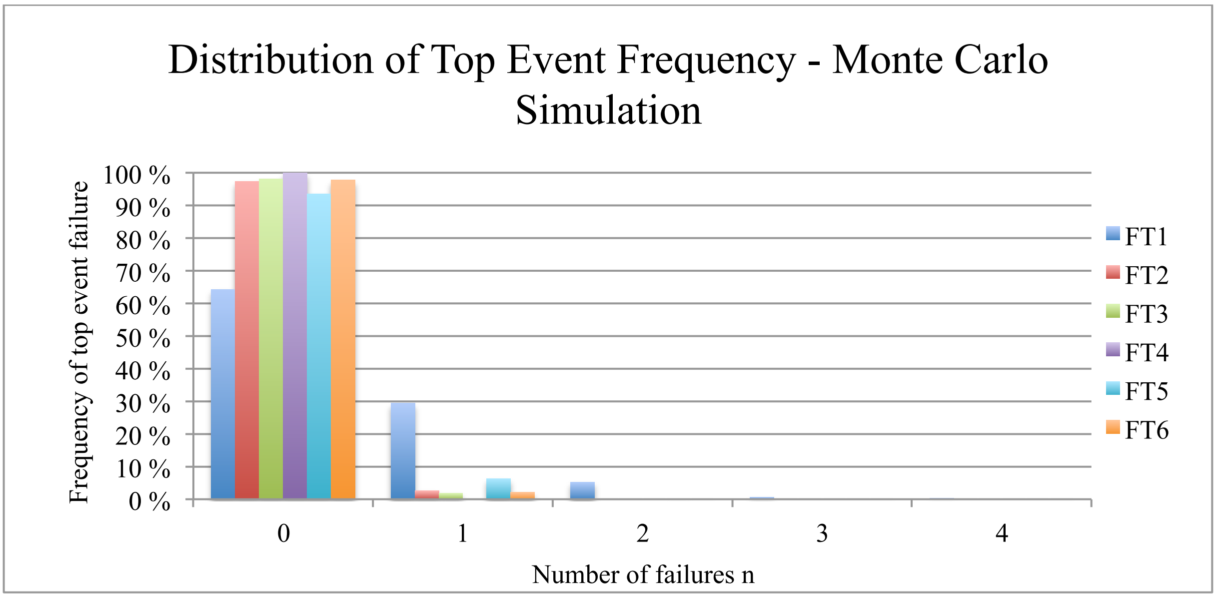


Figure 5.5: Distribution of top event frequencies of fault trees calculated by Monte Carlo simulation

Table 5.15 lists the frequencies of the top events calculated by hand calculation (upper bound approximation), numerical integration, and Monte Carlo simulation. The frequencies are given as occurrence per hour.

Table 5.15: Frequencies of top event per fault tree

	Frequency of Top Event (occurrence per hour)		
Fault Tree	Hand Calculation	Numerical Integration	Monte Carlo Simulation
F1	4.04E-05	4.04E-05	4.94E-05
F2	2.24E-06	2.24E-06	2.97E-06
F3	2.18E-06	2.18E-06	2.17E-06
F4	8.62E-11	8.37E-11	0
F5	7.44E-06	7.43E-06	7.42E-06
F6	2.24E-06	2.24E-06	2.51E-06

5.2.4.2 Event Tree Results

As stated in Section 3.1.3, an event tree diagram displays the possible accident scenarios/event sequences which may follow a specific hazardous event. The results of the three event trees modelled in Section 5.2.3 are attached from Appendix S to Appendix U. Table 5.16, Table 5.17, and Table 5.18 are the summarized consequence spectrums for the hazardous event in each event tree (ref. Section 3.1.5).

Table 5.16: Consequence spectrum for event tree one, Overpressure

i	Consequences (C_i)	Frequency per year
1	Leakage of washwater and an uncontrolled fire has broken out.	6.096E-14
2	Leakage of washwater, a fire has broken out, and the sprinklers do not work.	6.090E-11
3	Leakage of washwater, a fire has broken out, and the fire alarm does not work.	6.035E-12
4	Leakage of washwater, a fire has broken out, and the fire protection works.	6.029E-09
5	Leakage of washwater and no fire has broken out.	4.064E-09
6	No leakage of washwater and an uncontrolled fire has broken out.	9.144E-14
7	No leakage of washwater, a fire has broken out, and the sprinklers do not work.	9.135E-11
8	No leakage of washwater, a fire has broken out, and the fire alarm does not work.	9.053E-12
9	No leakage of washwater, a fire has broken out, and the fire protection works.	9.044E-09
10	No leakage of washwater and no fire has broken out.	6.096E-09
11	High water level does not work, but automatic stop of water supply does work and further unwanted scenarios are averted.	2.515E-06
12	High water level does work and further unwanted scenarios are averted.	2.537E-03

Table 5.17: Consequence spectrum for event tree two, Hazards related to loading/discharging

i	Consequences (C_i)	Frequency per year
1	Electrical power protection and automation and control system do not work.	2.100E-18
2	Electrical power protection and scrubber alarm do not work. Control panel in engine room does work.	2.098E-15
3	Electrical power protection and control panel do not work. Scrubber alarm does work.	2.098E-15
4	Electrical power protection does not work. Automation and control system does work.	2.096E-12
5	Separate generator, switchboard, scrubber alarm, and control panel do not work. Local starter does work.	2.079E-16
6	Separate generator, switchboard, and scrubber alarm do not work. Local starter and control panel do work.	2.077E-13
7	Separate generator, switchboard, and control panel do not work. Local starter and scrubber alarm do work.	2.077E-13
8	Separate generator and switchboard do not work. Local starter, scrubber alarm, and control panel do work.	2.075E-10
9	Separate generator, local starter, scrubber alarm, and control panel do not work. Switchboard does work.	2.098E-15
10	Separate generator, local starter, and scrubber alarm do not work. Switchboard and control panel do work.	2.096E-12
11	Separate generator, local starter, and control panel do not work. Switchboard and scrubber alarm do work.	2.096E-12
12	Separate generator and local starter do not work. Switchboard, scrubber alarm, and control panel do work.	2.094E-09
13	Separate generator, scrubber alarm, and control panel do not work. Switchboard and local starter do work.	2.077E-13
14	Separate generator and scrubber alarm do not work. Switchboard, local starter, and control panel do work.	2.075E-10
15	Separate generator and control panel do not work. Switchboard, local starter, and scrubber alarm do work.	2.075E-10
16	Separate generator does not work. Switchboard, local starter, scrubber alarm and control panel do work.	2.073E-07
17	Separate generator does work and further unwanted scenarios are averted.	2.079E-05

Table 5.18: Consequence spectrum for event tree three, Purification failure

i	Consequences (C_i)	Frequency per year
1	Automation and control system and outlet monitoring protection do not work.	2.200E-13
2	Automation and control system does not work. Outlet monitoring protection does work.	2.178E-11
3	Scrubber alarm and outlet monitor 1.4 do not work. Control panel does work.	2.198E-10
4	Scrubber alarm does not work. Control panel and outlet monitor 1.4 do work.	2.176E-08
5	Scrubber alarm does work and further unwanted scenarios are averted.	2.198E-05

5.3 Step 3: Risk Control Options (RCOs)

In this section the results from Step 2 is extracted to propose effective and practical risk control measures of the given open loop system. The objective of Step 3 is to focus on the activities/systems with high risks or with other particular concerns (ref. Section 3.2.4).

5.3.1 Focus on Risk Areas Needing Control

The results of the fault trees and the event trees form the basis of finding the risk areas that need control. Among the six fault trees, fault tree one, Overpressure in scrubber device and venturi, and fault tree five, Washwater not purified, have the highest top event probabilities to occur at a given point in time. For instance, their values of mean time to the first system failure (MTTF) are considerably lower than the residual fault trees (ref. Table 5.14). Additionally, Figure 5.5 illustrates clearly the observation by the distribution of top event frequency of the six fault trees.

The event trees also indicate risk areas needing control. Table 5.19 below lists the areas needing control based on the consequence category of material damage, while Table 5.20 ranks other concerned areas with high probability regardless of the severity.

Table 5.19: Areas needing control based of material damage

Material Damage	Event Tree	Hazardous Event	i	Consequence	Frequency per year
5	Overpressure	F1	6	No leakage of washwater and an uncontrolled fire has broken out.	9.144E-14
5	Overpressure	F1	1	Leakage of washwater and an uncontrolled fire has broken out.	6.096E-14
4	Overpressure	F1	7	No leakage of washwater, a fire has broken out, and the sprinklers do not work.	9.135E-11
4	Overpressure	F1	2	Leakage of washwater, a fire has broken out, and the sprinklers do not work.	6.090E-11
4	Overpressure	F1	8	No leakage of washwater, a fire has broken out, and the fire alarm does not work.	9.053E-12
4	Overpressure	F1	3	Leakage of washwater, a fire has broken out, and the fire alarm does not work.	6.035E-12
4	Purification failure	F5	1	Automation and control system and outlet monitoring protection do not work.	2.200E-13
4	Hazards related to loading/discharging	F2	2	Electrical power protection and scrubber alarm do not work. Control panel in engine room does work.	2.098E-15
4	Hazards related to loading/discharging	F2	3	Electrical power protection and control panel do not work. Scrubber alarm does work.	2.098E-15
4	Hazards related to loading/discharging	F2	1	Electrical power protection and automation and control system do not work.	2.100E-18

Table 5.20: Areas needing control based on probability

Material Damage	Event Tree	Hazardous Event	i	Consequence	Frequency per year
2	Overpressure	F1	12	High water level does work and further unwanted scenarios are averted.	2.537E-03
1	Purification failure	F5	5	Scrubber alarm does work and further unwanted scenarios are averted.	2.198E-05
1	Hazards related to loading/discharging	F2	17	Separate generator does work and further unwanted scenarios are averted.	2.079E-05
2	Overpressure	F1	11	High water level does not work, but automatic stop of water supply does work and further unwanted scenarios are averted.	2.515E-06
2	Hazards related to loading/discharging	F2	16	Separate generator does not work. Switchboard, local starter, scrubber alarm and control panel do work.	2.073E-07
2	Purification failure	F5	4	Scrubber alarm does not work. Control panel and outlet monitor 1.4 do work.	2.176E-08
3	Overpressure	F1	9	No leakage of washwater, a fire has broken out, and the fire protection works.	9.044E-09
2	Overpressure	F1	10	No leakage of washwater and no fire has broken out.	6.096E-09
3	Overpressure	F1	4	Leakage of washwater, a fire has broken out, and the fire protection works.	6.029E-09
3	Overpressure	F1	5	Leakage of washwater and no fire has broken out.	4.064E-09
2	Hazards related to loading/discharging	F2	12	Separate generator and local starter do not work. Switchboard, scrubber alarm, and control panel do work.	2.094E-09
3	Purification failure	F5	3	Scrubber alarm and outlet monitor 1.4 do not work. Control panel does work.	2.198E-10
2	Hazards related to loading/discharging	F2	14	Separate generator and scrubber alarm do not work. Switchboard, local starter, and control panel do work.	2.075E-10
2	Hazards related to loading/discharging	F2	15	Separate generator and control panel do not work. Switchboard, local starter, and scrubber alarm do work.	2.075E-10
3	Hazards related to loading/discharging	F2	8	Separate generator and switchboard do not work. Local starter, scrubber alarm, and control panel do work.	2.075E-10

Risk levels, probability, severity and confidence, provide suggestions for that fault tree one, Overpressure in scrubber device and venturi, fault tree two, No seawater to scrubber device and venturi, and fault tree five, Washwater not purified, are investigated further. Vesely-Fussell's measure of reliability importance in software CARA-FaultTree is employed to list the most critical basic events in each fault tree (ref. Section 4.3.1). Table 5.21-.23 display the generated results. Only basic events with reliability importance greater than 10^{-4} are considered to be critical, and the residual basic events are not included in these results. It should be noted that the results are in relevance with the cuts sets with one component presented in Appendix L.

Table 5.21: Reliability importance in fault tree one, Overpressure in scrubber device and venturi

Basic event	Reliability importance	Component ID	Component	Failure mode
Basic 38	1.45E-01	3.15	Drainpipe	PLU
Basic 33	1.21E-01	3.5	Injection nozzle	Looseness
Basic 34	1.21E-01	3.6	Injection nozzle	Looseness
Basic 35	1.21E-01	3.7	Injection nozzle	Looseness
Basic 36	1.21E-01	3.13	Injection nozzle	Looseness
Basic 37	1.21E-01	3.14	Injection nozzle	Looseness
Basic 3	1.14E-01	3.16	Exhaust outlet	PLU
Basic 6	2.89E-02	1.1	Inlet monitor	FTF
Basic 2	2.29E-02	2.22	Manual gate valve	FTC
Basic 1	2.29E-02	2.1	Manual gate valve	FTC
Basic 4	2.29E-02	1.2	Manual gate valve	FTC
Basic 5	2.29E-02	1.3	Manual gate valve	FTC
Basic 7	1.61E-02	1.1	Inlet monitor	SPO

Table 5.22: Reliability importance in fault tree two, No seawater to scrubber device and venturi

Basic event	Reliability importance	Component ID	Component	Failure mode
Basic 1	5.00E-01	2.1	Manual gate valve	FTO
Basic 2	5.00E-01	2.22	Manual gate valve	FTO
Basic 12	1.30E-04	2.3	Centrifugal pump	UST
Basic 18	1.30E-04	2.7	Centrifugal pump	UST
Basic 24	1.30E-04	2.11	Centrifugal pump	UST
Basic 30	1.30E-04	2.15	Centrifugal pump	UST
Basic 36	1.30E-04	2.19	Centrifugal pump	UST
Basic 17	1.03E-04	2.7	Centrifugal pump	FTS
Basic 11	1.03E-04	2.3	Centrifugal pump	FTS
Basic 23	1.03E-04	2.11	Centrifugal pump	FTS
Basic 29	1.03E-04	2.15	Centrifugal pump	FTS
Basic 35	1.03E-04	2.19	Centrifugal pump	FTS

Table 5.23: Reliability importance in fault tree five, Washwater not purified

Basic event	Reliability importance	Component ID	Component	Failure mode

Basic 2	2.63E-01	1.1	Inlet monitor	FTF
Basic 6	2.63E-01	1.4	Outlet monitor	FTF
Basic 3	1.47E-01	1.1	Inlet monitor	SPO
Basic 7	1.47E-01	1.4	Outlet monitor	SPO
Basic 1	5.26E-02	1.1	Inlet monitor	AOL
Basic 5	5.26E-02	1.4	Outlet monitor	AOL
Basic 4	3.10E-02	4.35	Control valve	AIR
Basic 8	3.10E-02	6.2	Control valve	AIR
Basic 19	5.62E-03	4.24	Hydrocyclone	PLU
Basic 23	5.62E-03	4.31	Hydrocyclone	PLU
Basic 11	5.62E-03	4.10	Hydrocyclone	PLU
Basic 15	5.62E-03	4.17	Hydrocyclone	PLU
Basic 20	8.02E-04	4.24	Hydrocyclone	STD
Basic 24	8.02E-04	4.31	Hydrocyclone	STD
Basic 12	8.02E-04	4.10	Hydrocyclone	STD
Basic 16	8.02E-04	4.17	Hydrocyclone	STD
Basic 14	4.09E-04	4.17	Hydrocyclone	ELP
Basic 10	4.09E-04	4.10	Hydrocyclone	ELP
Basic 22	4.09E-04	4.31	Hydrocyclone	ELP
Basic 18	4.09E-04	4.24	Hydrocyclone	ELP

5.3.2 Identify Potential Risk Control Measures

Risk control options have the objective of improving the availability of the open loop system. The options are established on the basis of the areas needing control and by expert judgement by the author. The following risk control measures are identified for further assessment:

1. Improve the knowledge on corrective maintenance and increase the quantity of spare parts
2. Review the preventive maintenance and procedures given in safety manual
3. Redundancy in inlet monitor and outlet monitor
4. The joints between nozzles, pipelines, and scrubber casing should be reinforced

By improving the knowledge on corrective maintenance on the various components, the machinists onboard the vessels could reduce the mean time to repair (MTTR). Together with increasing the quantity of spare parts, it is assumed that the MTTR of the critical basic events would be reduced by 10%.

By reviewing the maintenance guidance given in the safety manual, reduced numbers of failures are expected. It is presumed that a 5% reduction of the total number of failures divided by the total time in service, $\lambda/1E6$, by increasing and improving activities. Testing, inspection, cleaning, lubrication, replacement of parts, condition monitoring, and overhauling are examples of applicable activities. The reduction also influences the likelihoods of the barriers given in the event trees.

If the inlet and outlet monitors are not functioning, pH, PAH, turbidity and temperatures are not being monitored and the system is not fulfilling its purpose. Hence, a solution is to install a parallel monitoring system, both in the inlet and outlet. The new fitted monitors are given the same reliability as the existing inlet monitor 1.1 and outlet monitor 1.4.

The looseness's of the five injection nozzles are assumed to be critical both in Step 1 and Step 2. The joints between nozzles, pipeline and scrubber casing should be reinforced. Therefore, it is presumed a 5% reduction of the total number of failures divided by the total time in service, $\lambda/1E6$. The amendment is implemented in both injection nozzles and drainpipe 3.15. Additionally, the adjustment leads to that a koon-gate (with four out of six) is placed in exchange for OR-gate number 12 in fault tree one, Overpressure in scrubber device and venturi.

Other changes than within corrective and preventive maintenance on valves, hydrocyclones, and centrifugal pumps are not introduced on the grounds of the existing redundancies within the system.

The different proposed risk control measures affect the fault trees and event trees modelled in Step 2, resulting in changes to the availability probabilities of the system and material damages. Table 5.24 gives the percentage decrease of the system's unavailability when adopting the different risk control measures together with the increase in average availability in each fault tree.

Table 5.24: Change of unavailability and average availability after implementing risk control measures

	Decrease in Unavailability					Average Availability		
Fault Tree	RCO 1	RCO 2	RCO 3	RCO 4	All RCOs	Without RCOs	With RCOs	Increase
1	10%	5%	4%	75%	82%	0.999742	0.999956	0.0214%
2	10%	5%	0%	0%	15%	0.999994	1	0.0006%
3	0%	0%	0%	0%	0%	0.999990	0.999990	0%
4	2%	1%	11%	0%	11%	1	1	0%
5	9%	5%	92%	0%	94%	0.999971	1	0.0029%
6	10%	5%	0%	0%	15%	0.999972	0.999996	0.0024%

The average availabilities of fault tree two, No seawater to scrubber device and venturi, and fault tree five, Washwater not purified, are increased to 1 when all risk control options are implemented. The two fault trees are respectively adopted in event tree two, Hazards related to loading/discharging operations, and event tree three, Purification failure, which give an average unavailability equal to 0 in each event tree. Therefore, it is only necessary to look at the frequencies in event tree one, Overpressure, where fault tree one, Overpressure in scrubber device and venturi, is the initiating event. The reductions of frequency per end event in the event tree after adopting all risk control measures are given in Table 5.25.

Table 5.25: Frequency reduction per end event in event tree one, Overpressure

	Frequency per year				Frequency per year		
i	Without RCOs	With all RCOs	Reduction	i	Without RCOs	With all RCOs	Reduction
1	6.096E-14	7.763E-16	98.73%	7	9.135E-11	1.332E-12	98.54%
2	6.090E-11	8.163E-13	98.66%	8	9.053E-12	1.321E-13	98.54%
3	6.035E-12	8.094E-14	98.66%	9	9.044E-09	1.389E-10	98.46%
4	6.029E-09	8.511E-11	98.59%	10	6.096E-09	1.059E-10	98.26%
5	4.064E-09	6.489E-11	98.40%	11	2.515E-06	4.140E-08	98.35%
6	9.144E-14	1.267E-15	98.61%	12	2.537E-03	4.396E-05	98.27%

5.3.3 Group Risk Control Measures into Practical Regulatory Options

The risk control measures are grouped in different categories, which are based on the practical type of regulatory options. As elaborated in Section 3.2.4, there is a range of possible approaches. The risk control options are categorised in the following risk control measures:

- Procedural risk control: Improve the knowledge on corrective maintenance and increase the quantity of spare parts, and review the preventive maintenance given in safety manual.
- Redundant risk control: Redundancy in inlet monitor and outlet monitor.
- Engineering risk control: The joints between nozzles, pipelines and scrubber casing should be reinforced.

5.4 STEP 4: COST-BENEFIT ANALYSIS

The purpose of Step 4 is to identify and compare benefits and costs associated with implementing each risk contribution option identified in Step 3 (ref. Section 3.2.5).

5.4.1 PROBLEM DEFINITION

The first stage in Step 4 is to make a problem definition based on the two previous steps and additional boundaries. Only the most critical fault trees within each accident category are considered. Table 5.26 presents the difference in unavailability's after implementing the risk control options. The baseline in the cost-benefit analysis is set to be 25 years, as the costs should express the life cycle costs. The vessel with the open loop system is assumed to be operating in an Emission Control Area (ECA). Hence, the system is operational 100%, except during maintenance.

Table 5.26: Difference in unavailability after implementation of risk control option

	Difference in Unavailability			
Accident Category	RCO1	RCO2	RCO3	RCO4
Overpressure	1.97E-05	1.01E-05	9.04E-06	1.51E-04
Hazards related to loading/discharging operations	1.35E-06	6.61E-07	0.00E+00	0.00E+00
Purification failure	2.08E-06	1.12E-06	2.04E-05	0.00E+00
Total Δunavailability	2.31E-05	1.18E-05	2.94E-05	1.51E-04

5.4.2 IDENTIFY COSTS AND BENEFITS

There are several effects on the open loop system by implementing risk control options, both negative and positive. The assumed costs and benefits involved per risk control option are elaborated in this section. It should be noted that capital expenses for the open loop system are not included; equipment, design, training/documents and installing costs are equal when the open loop system is installed.

Improving knowledge on corrective maintenance requires more education for the crew, and thus accrue training costs. However, the benefit is a reduction in maintenance time when a failure has occurred. Larger quantities of spare parts give higher purchase costs, but the profit is reduced downtime due to availability of spare parts and quick corrective maintenance.

Reviewing the preventive maintenance in the safety manual would lead to several expenses. Increased level of testing, inspection, cleaning, and lubrication result in costs concerning training and maintenance. Further, it is assumed replacement of parts, condition monitoring and overhauling, add additional installation and commissioning costs, and maintenance costs. The profitability is better prepared crew and reduced number of failures.

Installing parallel monitoring systems would first of all require investment cost, and installation and commissioning cost. Besides, it is expected that the installation require time in port or dock, which again would result in downtime costs. It is assumed that the crew already have training in how to operate and perform maintenance on the monitoring systems. Hence, training cost is not included as an expense. As the other risk control options, the benefit would be reduced number of failures.

Reinforcement of the joints demand equipment and steel. Therefore, it is assumed there will be investment cost, in addition to downtime cost due to the work needing to be done. The benefit is reduction of nozzles falling down and reduced numbers of system failures.

5.4.3 QUANTIFY COSTS AND BENEFITS

According to the article *Exhaust Gas Cleaning Systems Selection Guide*, typical containerships sailing in ECA with open loop systems are estimated to have low and high equipment price (CAPEX) respectively at $3,795,000 and $5,566,000 (The Glosten Associates 2011). Low and a high cost estimates are established to take account of factors such as variability in cost globally and since the proposed technical solutions are not specified in detail. The various costs per risk control option are estimated as percentages of the equipment prices, and are set by expert judgement by the author on the basis of several literature sources, which are presented below Table 5.27.

Table 5.27: Cost percentage of low and high equipment price per risk control option

	RCO 1		RCO 2		RCO 3		RCO 4	
Cost	Low	High	Low	High	Low	High	Low	High
Downtime	0%	0%	0%	0%	70%	90%	40%	50%
Installation and commissioning	0%	0%	0%	0%	15%	25%	0%	0%
Investment/purchase	10%	10%	10%	10%	40%	40%	10%	10%
Maintenance	0%	0%	3%	4%	0%	0%	0%	0%
Training	2%	2%	2%	2%	0%	0%	0%	0%

Risk control options number three and four are expected to have downtime costs. Both of the two options requires shutdown of the system, due to the extent of work and since the preparatory work cannot take place while the vessel is sailing. The reasons are that the reinforcement will take place inside the scrubber device and the existing monitors have to be shut down in order to install the monitors. The physical drivers of repairs and maintenance (R&M) sector are the survey cycles, routine onboard work and casualty and incident damage

(Drewry Maritime Research 2015). Though the installation may take place when other scheduled surveys or maintenance work are preformed, additional downtime is expected. This because of the different ship sizes and extent, and estimated installation time, low and high cost percentages are set to be unequal. Reinforcement is projected to demand less time than installing parallel monitors. Therefore, risk control option number three is given to have downtime costs at 70% and 90%, while risk control option number four is assumed to have costs at 40% and 50%.

Exhaust Gas Cleaning Systems Selection Guide states that installation of an open loop system with low expenses costs 40%, while an open loop system with high expenses costs 60% of the equipment cost of the system itself (The Glosten Associates 2011). On this basis of this, the installation and commissioning costs in risk control option number three is set respectively to be 15% and 25% of the equipment cost of the open loop system.

All the risk control options are set to have investment or purchase costs. Risk control option number one has purchase costs due to spare parts. In order to be able to have the necessary spare parts accessible, they have to be purchased continuously. Maintenance and repair equipment of a low and high cost open loop system costs 2% and 6% of the equipment cost, respectively (The Glosten Associates 2011). However, risk control option number one is assumed to have significantly larger expenses (10%), because of the large demand for spare parts. Risk control option number two is given the same percentages, as there will be performed replacement of parts and overhauling. Risk control number three has high investment costs when installing inlet and outlet monitors. It is assumed that the monitors need overhauling every five year. Hence, the investment is not a one-time procurement. As the monitors are technical and complex, the low and high percentages are set to be 40% of the equipment cost of the open loop system. Risk control option number four invests in steel. Steel work is influenced by labour and steel cost trends (i.e. demand for steel products and the price of raw materials), and the price of steel is specified in $ per kg (Drewry Maritime Research 2015). An operational engineer is paid roughly $200,000 and $350,000 annually on a vessel with low and high open loop system expenses, respectively. Further, 25% and 75% of annual payment is engaged to operating an open loop system (The Glosten Associates 2011). In regards to labour cost of steel work, the steel investment in risk option number four is assumed to be equal to 10%.

Only risk control option number two has maintenance costs. In 2014, average repairs and maintenance costs of a container vessel with 70-75,000 dwt was $320 per day, while a container vessel with 170-180,000 dwt was $360 per day (Drewry Maritime Research 2015). Because of the low and high equipment costs and an assumption of maintenance work once a week, the maintenance expenses are assumed to be respectively 3% and 4%, per year.

The first and second risk control options require training of the crew to improve corrective and preventive maintenance. According to *Exhaust Gas Cleaning Systems Selection Guide*, training/documents are given to cost 2% of an open loop system. The same approximation is expected in this context.

The costs are calculated with a 25-year perspective. Expenses spanning over several years, such as maintenance, are calculated by extracting the compound-amount factor for equal-payment-series (Ayyub 2003). The factor is shown in the equation below, where A is payment, n is the amount of years and i is the interest rate. However, in this situation, it is more appropriate to use the term discount rate rather than interest rate. The discount rate represents the time value of money to a company. It is set to be 12% based on an example of discounted cashflow analysis for tanker charter options (Stopford 2009). The total cost calculations of each risk control option are presented in Appendix W, while the total costs per risk control option through 25 years are presented in Table 5.28.

$$F = A\frac{(1+i)^n - 1}{i} \tag{5.1}$$

Table 5.28: Total cost per risk control option through 25 years

RCO	Type of Expense	Total Cost [$]	RCO	Type of Expense	Total Cost [$]
1	Low	6 072 024	3	Low	2 371 875
	High	89 056 358		High	43 136 500
2	Low	7 590 031	4	Low	189 750
	High	118 741 811		High	3 339 600

5.4.4 ADAPTION ON TO A COMMON SCALE

A transformed version of the Implied Cost of Averting a Fatality (ICAF) is utilised to adopt the different risk control measures onto a common scale (ref. Section 3.2.5). Since fatalities are not considered in this master thesis, the risk reduction per ship in terms of the number of fatalities averted, ΔR, in the dominator is replaced with the difference of unavailability. Thus, the reformed common scale, referenced as CS, is the following:

$$CS = \frac{RCO\ cost}{\Delta unavailability} \tag{5.2}$$

The preferable result after implementing a risk control option is to get a significant change in unavailability, at the same time as having low costs. Therefore, it is desirable to achieve a low as possible CS. The calculated values of CS per risk control option are presented in Table

5.29. Figure 5.6 shows the distributions of risk control options on grounds of total costs and the unavailability after implementing of risk control options.

Table 5.29: CS of risk control options

		Cost of RCO [$]		CS [$×10^3]	
RCO	Δ unavailability	Low	High	Low	High
1	2.31E-05	6072024	89056358	263165797	3859765028
2	1.18E-05	7590031	118741811	641646002	10038195225
3	2.94E-05	2371875	43136500	80556829	1465060200
4	1.51E-04	189750	3339600	1260730	22188854

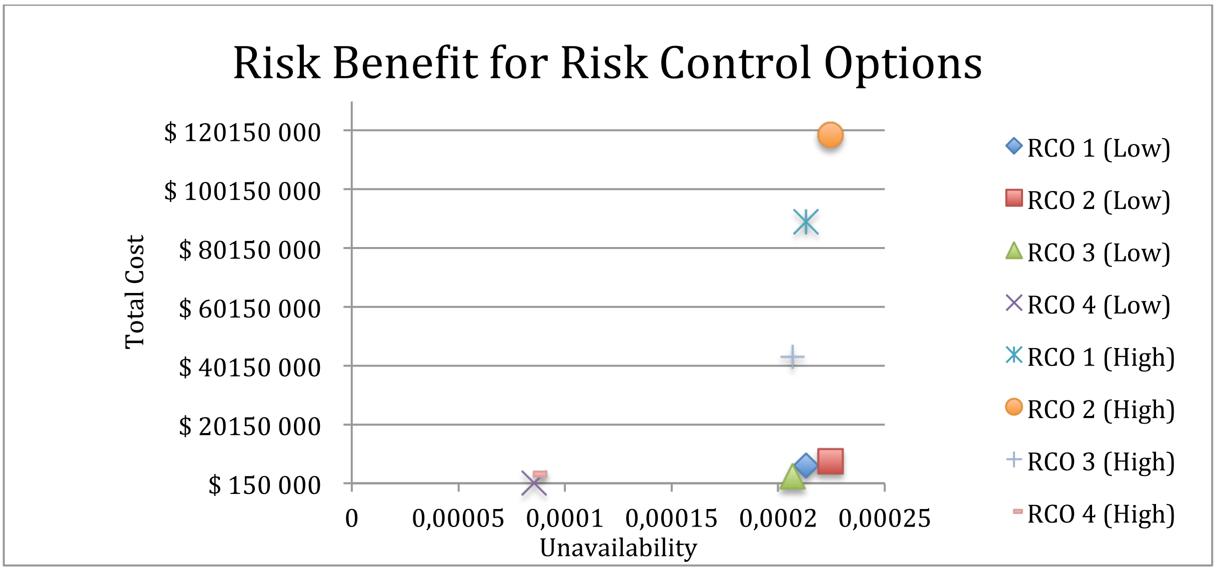


Figure 5.6: Risk benefit for risk control options

5.4.5 Evaluating Uncertainty

There are various uncertainties in this cost-benefit analysis. Identifying the costs and benefits is quite difficult without any experiences or more sources on the open loop system. The assumed downtime depends on many factors, as previously mentioned. Realistically, the downtime could cost more than the high and low equipment prices if complications occur or if the extent of work is larger than assumed. The installation cost in risk control option number three is given to be less than the installation costs of the whole system, and there are uncertainties to how large a share the monitors take of the entire system. Instead of assuming the percentages of investment/purchase costs, costs from suppliers or Wärtsilä are more convenient and preferable. Additionally, a vessel is complex and it is therefore more accurate to use maintenance costs from open loop systems rather than daily average repairs and maintenance costs of a container vessel.

5.5 STEP 5: RECOMMENDATIONS FOR DECISION-MAKING

The previous three steps in the Formal Safety Assessment lay the foundation for the cost-benefit analysis in Step 4. Thus, the recommendations are first and foremost centred on the analysis in Step 4. Based on Table 5.28, the following risk control options are considered to improve the systems reliability in a cost-effective manner and are therefore recommended:

- Redundancy in inlet monitor and outlet monitor (RCO 3)
- The joint between nozzles, pipelines and scrubber device should be reinforced (RCO 4)

As previous mentioned, it is desirable to achieve a low as possible CS, which risk control option number three and four have compared to the other two options. The improvements by these control options on the modelled fault trees are seen in Table 5.24. Both of the options increase the availability of fault tree one, Overpressure in scrubber device and venturi, and fault tree five, Washwater not purified, which are found to be the most critical top events in Step 2. Figure 5.6 illustrates that risk control option number four is the best choice concerning cost. Besides, Table 5.29 acknowledges the option has the lowest value of CS compared to the other risk control options, caused by its large change in unavailability and low value of costs. The residual risk control options have higher unavailability's. Therefore, among the three options, a cost-conscious decision maker should chose risk control option number three; it has significant lower cost both in terms of low and high costs.

6 DISCUSSION

The execution of the Formal Safety Assessment and the results are discussed in the two following sections. The main drawback of the study is that there are not found any previous Formal Safety Assessments of open loop systems, which sets limitations on the discussion of the results. With that in mind, it is very difficult to draw a conclusion on whether the results are credible.

6.1 EXECUTION OF FORMAL SAFETY ASSESSMENT

There are made several assumptions through the Formal Safety Assessment (FSA). As mentioned in Section 3.2.1, the interactions are in reality not as simple as following the five steps. This analysis is performed from Step 1 to Step 5 with no repeated iterations. However, the steps and the results are evaluated along the execution, and it is considered that the analysis is performed in accordance with the methodology.

The neglect of a few components (e.g. bypass arrangement, tank air vent) is not considered to limit the analysis compared to the fact that the P&ID of the open loop system manufactured by Wärtsilä is a preliminary version. Though these elements reduce the accuracy of an actual open loop system, it is preferable to set the boundaries early rather than making false assumptions along the analysis.

Step 1 and Step 2 utilises reliability data from the handbook *Offshore Reliability Data* (OREDA), which generally does not cover the entire lifetime of equipment, but typically two to four years of operation. The burn-in phase is not included in the OREDA database, and the items are often replaced or refurbished before they reach the wearout phase (SINTEF 2009). Hence, certain failure modes, failure causes, and reliability data (i.e. total number of failures divided by the total time in service, n/λ and active repair time) might result in incorrect and forgotten potential failure modes, and also unlikely probability assumptions. Moreover, there are sources of errors by extracting reliability data other than scrubber environment. The experience data are from topside equipment in the offshore industry, and consequently, the data input are believed to be of a hypothetical nature.

Though the FMECA and the risk matrix are results of a shorter version of DNV GL's Technology Qualification Process, the approach is considered to have the same objective and standard of hazard identification and screening as Step 1 in the Formal Safety Assessment. Moreover, the structure of the FMECA is considered to be sufficient on its own, but it is difficult to distinguish a component with a given failure mode to a component in another position with the same failure mode. Nevertheless, additional aspects are assessed and the results revaluated quantitatively in Step 2.

The fault trees are modelled on the basis of the preliminary and simplified P&ID, and by expert judgement by the author. Therefore, due to reduced accuracy of an actual open loop system, there is a chance of misinterpretation. I.e., other potential fault trees within each accident category might be overseen, and wrong assessments on boundary conditions might have been made. These two aspects could result in an inconsistent analysis. In fault tree one, Overpressure in scrubber deice, exhaust outlet 3.16 is considered to be blocked by impurities. Usually, the exhaust outlet of a scrubber system with 4 MW has approximately a diameter of 850 mm (Wärtsilä 2014). Hence, large masses of impurities are needed in order to block the outlet, and thus a lower probability would have been more suitable. Moreover, pipeline 2.23 is only considered once in fault tree two, No seawater to scrubber device and venturi, and is not included in any other fault trees. Pipelines should consistently be included where they are applicable. Apart from this discrepancy, the boundary conditions are defined and obeyed to obtain a consistent fault tree analyses.

It is important to bear in mind that the divagation of the availabilities between the six fault trees is not severely large. The average availabilities of the top events are at 0.999742 or higher, which is considered to be an appropriately good starting point. However, in this thesis, no failures are acceptable and improvements have to be recommended to the decision-makers.

Several assumptions are made along the modelling of the event trees, since there is no available accident information of scrubber accidents. Though credible sources are found regarding safety systems within scrubber systems, no external events are considered and the author sets the levels of material damage. Therefore, the event trees are not as realistic as preferable.

The risk control options in Step 3 are established by expert judgement by the author. The percentage reductions of corrective maintenance and preventive maintenance are roughly estimated. An improved insight in the maintenance procedures and documentations would increase the credibility of the two risk control options. Additionally, it is very difficult to know with certainty if reinforcing the joints in risk control option number four contributes to a 5% reduction of the total number of failures divided by the total time in service, $\lambda/1E6$.

As evaluated in Section 5.4.5, there are several uncertainties in the cost-benefit analysis in Step 4. The quantification of costs and benefits are set by expert judgement by the author on the basis of academic literature. Among others, it would be preferable to contact the manufacturer and shipowners to obtain more accurate costs. Technology develops rapidly, so workload and costs of software updates, new equipment, maintenance, and overhauling of the additional parallels of monitors are difficult to foresee and estimate with a time lapse of 25 years. It has to be pointed out that the costs of benefits are not included. The costs are neglected because of the benefit of all the risk control options is mainly reduced number of failures. On the other hand, with a better insight and consideration it is possible to distinguish between the different benefit costs. Moreover, the sources of costs of improvements are extracted on all risk control options, so it is assumed that the deviations are consistent. Hence, the total costs of the various risk control options are comparable.

6.2 Results

The results from Step 1 shows that of 153 FMECA IDs, 52% are ranked with low risk, 45% with medium risk and 3% with high risk. Drainpipe and injection nozzles are assumed to have the highest risk. Even though plugged/chocked, external leakage, fail to open on demand and fail to close on demand are the four mostly common failure modes, it does not necessary mean they are the most crucial failure modes; the numbers of failure modes reflect the large amount of pumps and valves. Though it is assumed that only the components with medium and high risk that have to be studied further, some components with low risk (e.g. inlet monitor with abnormal output) are included in the following steps due to its overall position and importance.

The quantitative analysis in Step 2 confirms that drainpipe and injection nozzles are critical and are of great importance within the open loop system. The results from the six modelled fault trees shows that the most critical top events are overpressure in scrubber device and venturi, and washwater not purified. The reason why these two have the most frequent top events is because of an OR-gate increases the number of minimal cut sets in the fault tree, while an AND-gate increases the number of basic events in the cut sets. In brief this is because, the occurrence of the top event of a tree with an AND-gate is the multiplication of the occurrence probabilities of the basic events, while the occurrence of the top event of a tree with an OR-gate is the addition of probabilities of the basic events minus the multiplication of the occurrence probabilities of the basic events (ref. Section 3.1.2). An additional explanation is the high probabilities of minimal cut sets, which also is reflected in the hand calculations in Appendix L. Again, it is important to bear in mind that the divagations of the availabilities between the six fault trees are not severely large.

The end events in the event trees with high material damage have relative low frequencies per year. It is an effect of reliable safety systems within the scrubber system, and the low frequencies of the initiating events. Event tree number one, Overpressure, has the largest share of end events with high material damage. Overpressure could potentially bring out an explosion, causing major damages onboard. Since there is washwater inside the scrubber device, a fire could be prevented or slightly reduced. This element should be considered, and the probability of a fire should be lower than 60%, as decided in Section 5.2.3. First and foremost, the focus of improvement is on the fault trees (i.e. Overpressure in scrubber device and venturi, no seawater to scrubber device and venturi, and washwater not purified) when identifying and implementing risk control options. The event trees are only changed by the 5% reduction of the total number of failures divided by the total time in service, $\lambda/1E6$. In retrospect, the safety systems are of great importance and should be improved on an equal footing as the fault trees. However, the outcome would not improve significantly for the second event tree, Hazards related to loading/discharging operations, and the third event tree, Purification failure, since their initiating events are equal to 0.

The cost-benefit analysis shows that risk control option number four, reinforcement of joints between nozzles, pipelines and scrubber casing, is the best proposal concerning costs. However, the residual options have higher, and almost equivalent unavailability values after implementation, and it is therefore more challenging to distinguish between these options. It is assumed that a cost-conscious decision maker should then chose risk control option number three; it has a significantly lower cost both in terms of low and high costs. However, as previous stated, the additional parallels of monitors are difficult to foresee and estimate at time lapse of 25 years, and in reality the optimal option could be one of the other two options.

In order for the open loop system to meet the guidelines in resolution MEPC.184(59) the open loop system has to function 100%. By implementing the risk control options, it is assumed that the open loop system is significant adequate.

7 CONCLUSION

The objective of this master thesis was to evaluate an open loop system manufactured by Wärtsilä through Formal Safety Assessment to gain a greater understanding on the challenges this technology has in relation to system risks and safety.

On the basis of 153 cases of components with a specific failure mode in the FMECA, 52% are ranked with a low risk, 45% with a medium risk, and 3% with a high risk. The components in the scrubber system have the largest share of medium and high risks, where the drainpipe and the injection nozzles are the most critical components. A Risk Contribution Tree (RCT) was modelled and consist of six fault trees and three event trees, distributed within three accident categories (i.e. Overpressure, Hazards related to loading/discharging operations, Purification failure). The fault trees were constructed and quantitatively analysed in software CARA-FaultTree. The observations showed that the most critical top events are overpressure in scrubber device and venturi, and difficulties with purifying washwater. The end events with high material damage in event trees have relatively low frequencies per year, as an effect of reliable safety systems within the scrubber system and low frequencies of the initiating events. The following risk control options increase the reliability of the open loop system: improvement of corrective maintenance, review the preventive maintenance procedures, redundancy in inlet monitor and outlet monitor, and reinforcement of joints between nozzles, pipelines and scrubber casing. In a cost-benefit aspect, redundancy of monitors and reinforcement of joints are the most beneficial solutions to increase the open loop system's reliability in a feasible and safe matter.

Based on the results from the Formal Safety Assessment, it is concluded that the open loop system is considered to be highly reliable. However, with improvement of risk control options, as additional monitors and reinforcement of joints inside the scrubber device, the system increases its availability significantly. The adoption will increase the time of operation of the system, and assist the system to meet the guidelines in resolution MEPC.184(59). The results are applicable for shipowners, class societies, and manufactures. By knowing the critical components, the open loop system(s) can increase operation performance and reliability. The perfections are especially of great importance since the purpose of scrubbers is to meet the imposed limitations on sulphur oxides.

8 FURTHER WORK

To produce a more reliable inventory result, there are particular issues that should be further addressed. Firstly, the analysis can be performed with repeated iterations. The reliability data from OREDA should be replaced with experience data from existing open loop systems or at least a more similar environment. Besides, collaboration with a manufacturer or a shipowner can lead to better sources than the preliminary P&ID. These improvements would increase the accuracies of all the steps of the Formal Safety Assessment.

The method being adopted in Step 2, such as Risk Contribution Tree, should address several additional types of risks. Though it depends on the problem under consideration, further work could examine the risk to people and external damages on the environment. Greater insight in preventive and corrective maintenance can improve the basis of assuming reduction of risks and estimate costs. Overall, the costs estimations in Step 4 can be improved and additional costs might be included.

Another interesting aspect is to investigate the fees and fines of sailing in an ECA with a ship neglecting the restrictions up against how much a shipowner has to invest in an open loop system and additional risk control options. Nevertheless, the costs a shipowner has to pay if the ship experiences noncompliance with the emission standards, and the flag Administration declines the exemption should be studied. These involvements could affect the cost-benefit assessment in Step 4 and decision-making in Step 5.

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A. Scrubber Statistics from DNV GL

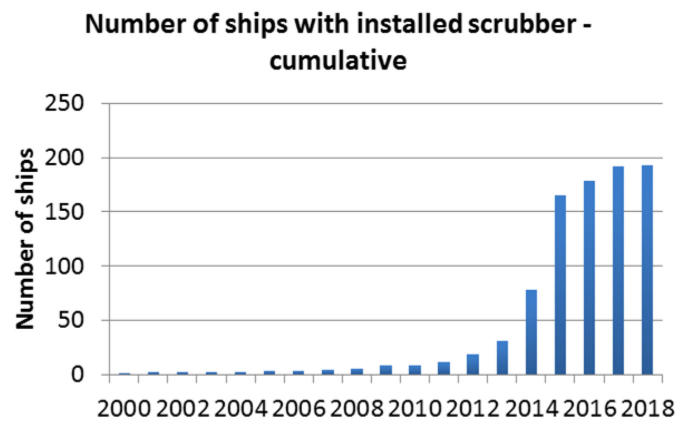


Figure A.1: Number of ships with installed scrubber - cumulative (DNV GL 2014)

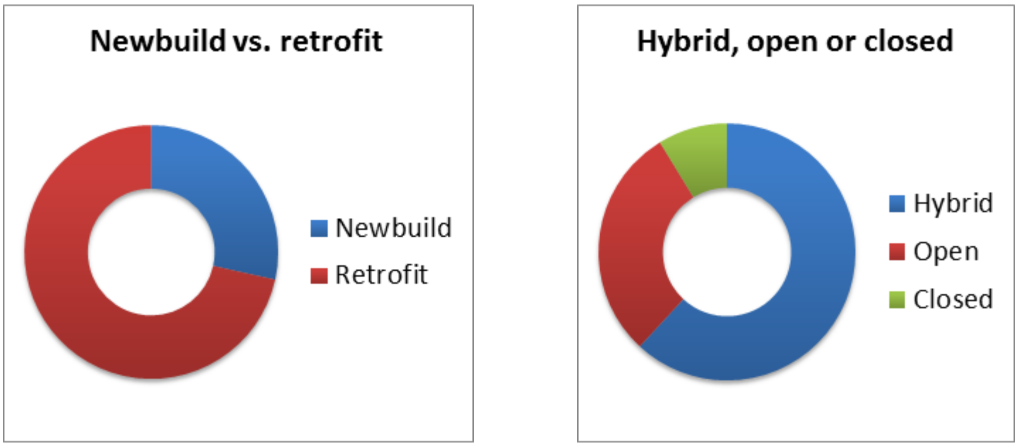


Figure A.2: a. Newbuild vs. retrofit b. Hybrid, open or closed (DNV GL 2014)

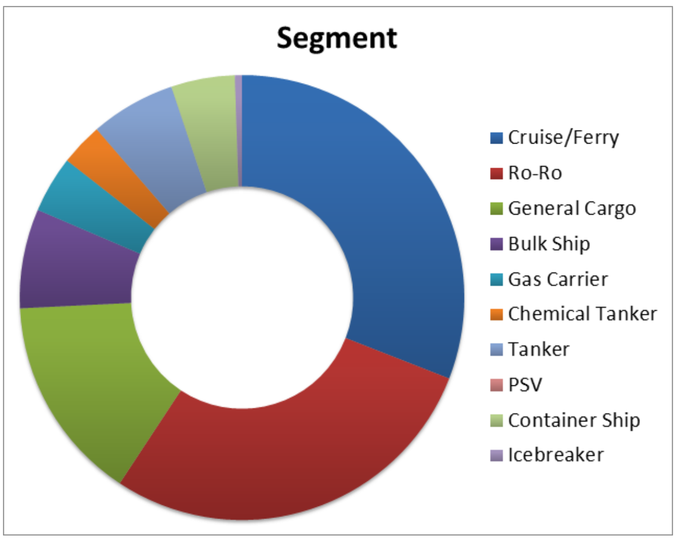


Figure A.3: Segment (DNV GL 2014)

B. EXAMPLE OF A RISK CONTRIBUTION TREE (RCT)

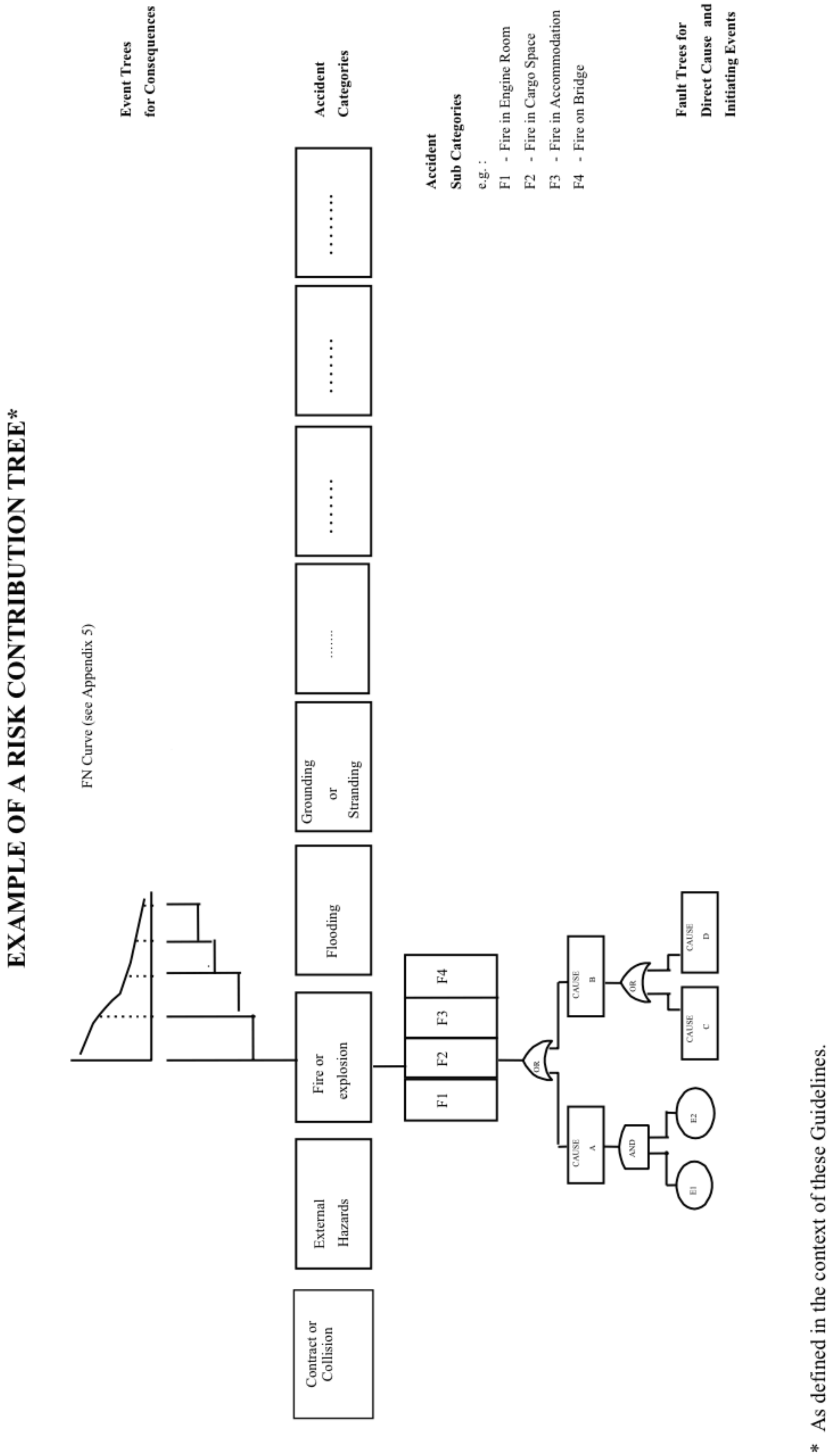


Figure B.1: Example of risk contribution tree (IMO 2002)

C. P&I DIAGRAM OF EXHAUST GAS SCRUBBER SYSTEM, WÄRTSILÄ

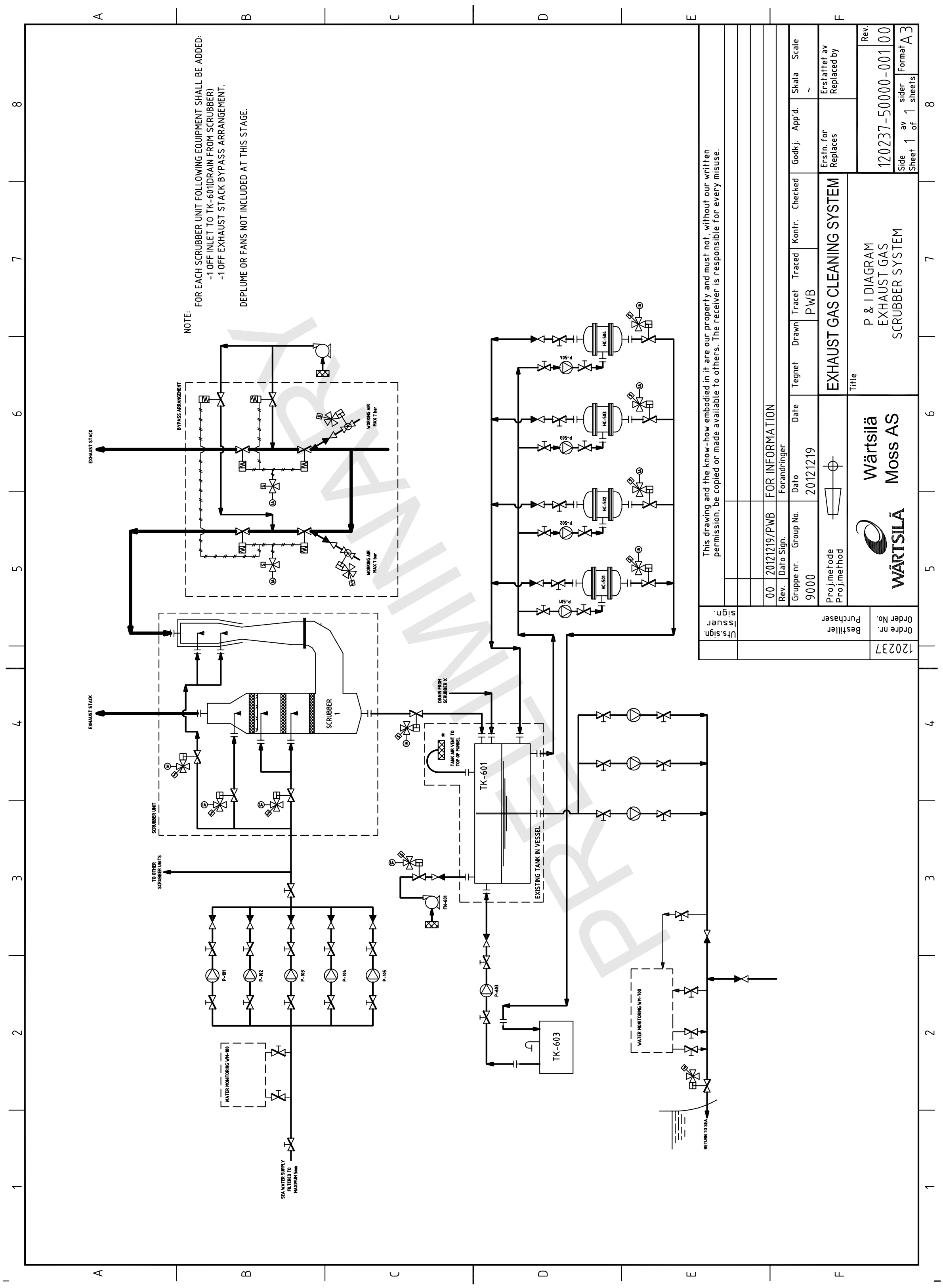


Figure C.1: P&I diagram exhaust gas scrubber system

D. P&I Diagram of Exhaust Gas Scrubber System, Wärtsilä with ID

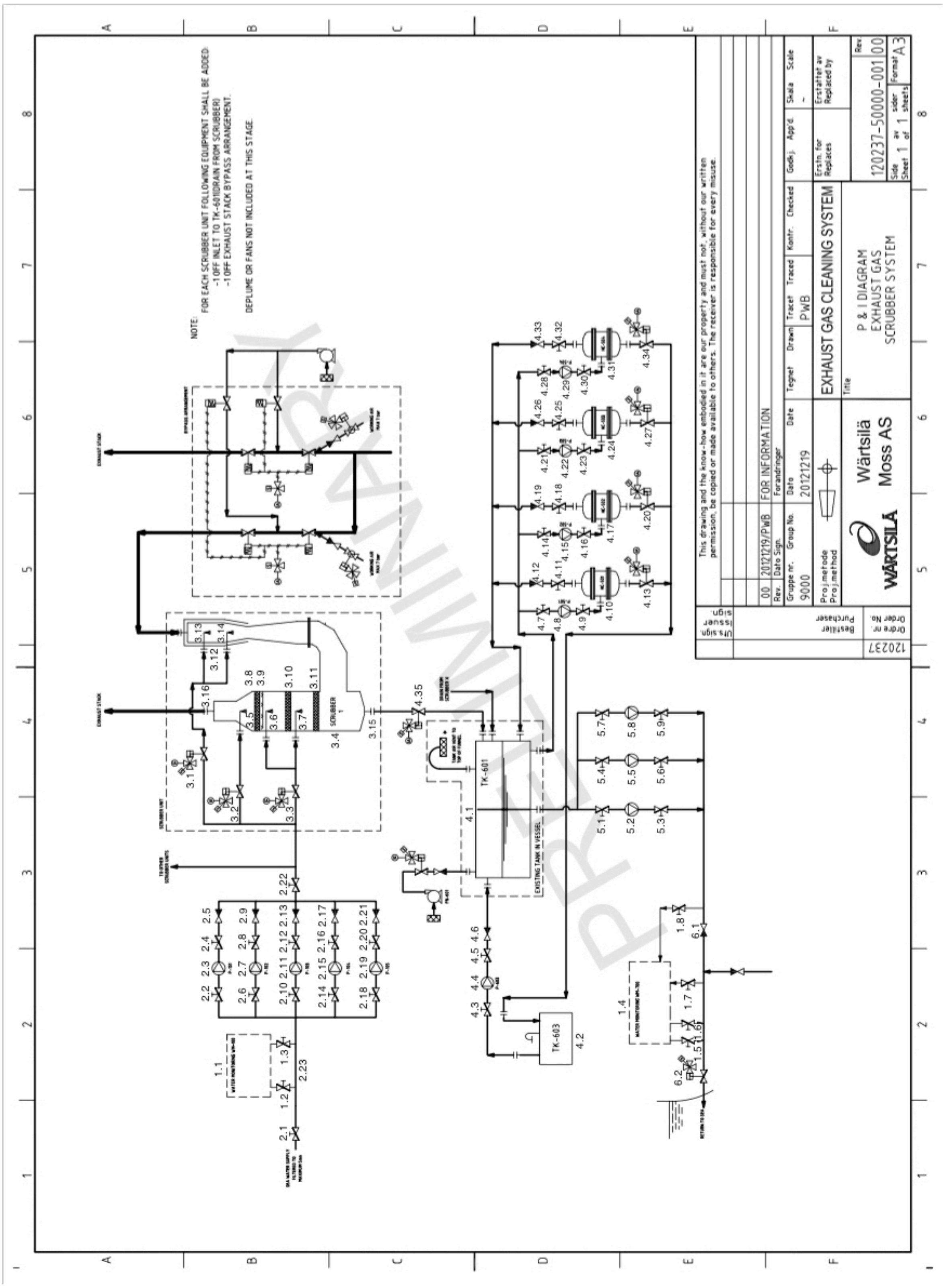


Figure D.1: P&I diagram exhaust gas scrubber system with component IDs

E. Symbol Description

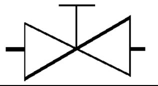
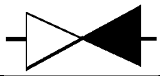
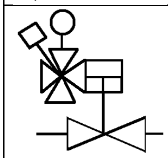
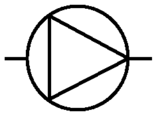
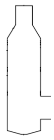
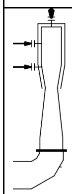
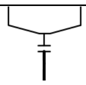
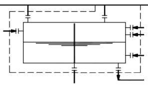
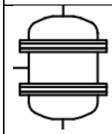
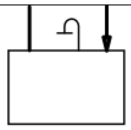
Symbol	Description
	Manual gate valve
	Check valve
	Control valve
	Pump
	Monitor
	Scrubber device
	Packed bed
	Droplet separator and steam cleaner
	Injection nozzle
	Venturi
	Drain pipe
	Residence tank
	Hydrocyclone
	Sludge tank

Figure E.1: Symbol description

F. MAIN FUNCTIONS AND SUB-FUNCTIONS

Table F.1: Main functions and sub-functions in exhaust gas scrubber system

ID	Component/function	ID	Component/function	ID	Component/function
1	Monitoring system	3.6	Injection nozzle	4.28	Manual gate valve
1.1	Inlet monitor	3.7	Injection nozzle	4.29	Pump
1.2	Manual gate valve	3.8	Steam cleaning	4.30	Manual gate valve
1.3	Manual gate valve	3.9	Droplet separator	4.31	Hydrocyclone
1.4	Outlet monitor	3.10	Packed bed	4.32	Manual gate valve
1.5	Manual gate valve	3.11	Packed bed	4.33	Check valve
1.6	Manual gate valve	3.12	Venturi	4.34	Control valve
1.7	Manual gate valve	3.13	Injection nozzle	4.35	Control valve
1.8	Manual gate valve	3.14	Injection nozzle	5	Scrubbing water supply pump outlet
2	Scrubbing water supply pump inlet	3.15	Drainpipe	5.1	Manual gate valve
2.1	Manual gate valve	3.16	Exhaust outlet	5.2	Pump
2.2	Manual gate valve	4	Water treatment system	5.3	Manual gate valve
2.3	Pump	4.1	Residence tank	5.4	Manual gate valve
2.4	Manual gate valve	4.2	Sludge tank	5.5	Pump
2.5	Check valve	4.3	Manual gate valve	5.6	Manual gate valve
2.6	Manual gate valve	4.4	Pump	5.7	Manual gate valve
2.7	Pump	4.5	Manual gate valve	5.8	Pump
2.8	Manual gate valve	4.6	Check valve	5.9	Manual gate valve
2.9	Check valve	4.7	Manual gate valve	6	Water outlet
2.10	Manual gate valve	4.8	Pump	6.1	Check valve
2.11	Pump	4.9	Manual gate valve	6.2	Control valve
2.12	Manual gate valve	4.10	Hydrocyclone		
2.13	Check valve	4.11	Manual gate valve		
2.14	Manual gate valve	4.12	Check valve		
2.15	Pump	4.13	Control valve		
2.16	Manual gate valve	4.14	Manual gate valve		
2.17	Check valve	4.15	Pump		
2.18	Manual gate valve	4.16	Manual gate valve		
2.19	Pump	4.17	Hydrocyclone		
2.20	Manual gate valve	4.18	Manual gate valve		
2.21	Check valve	4.19	Check valve		
2.22	Manual gate valve	4.20	Control valve		
2.23	Pipeline	4.21	Manual gate valve		
3	Scrubber system	4.22	Pump		
3.1	Control valve	4.23	Manual gate valve		
3.2	Control valve	4.24	Hydrocyclone		
3.3	Control valve	4.25	Manual gate valve		
3.4	Scrubber device	4.26	Check valve		
3.5	Injection nozzle	4.27	Control valve		

G. Schematic Block Diagram of Exhaust Gas Scrubber System, Wärtsilä

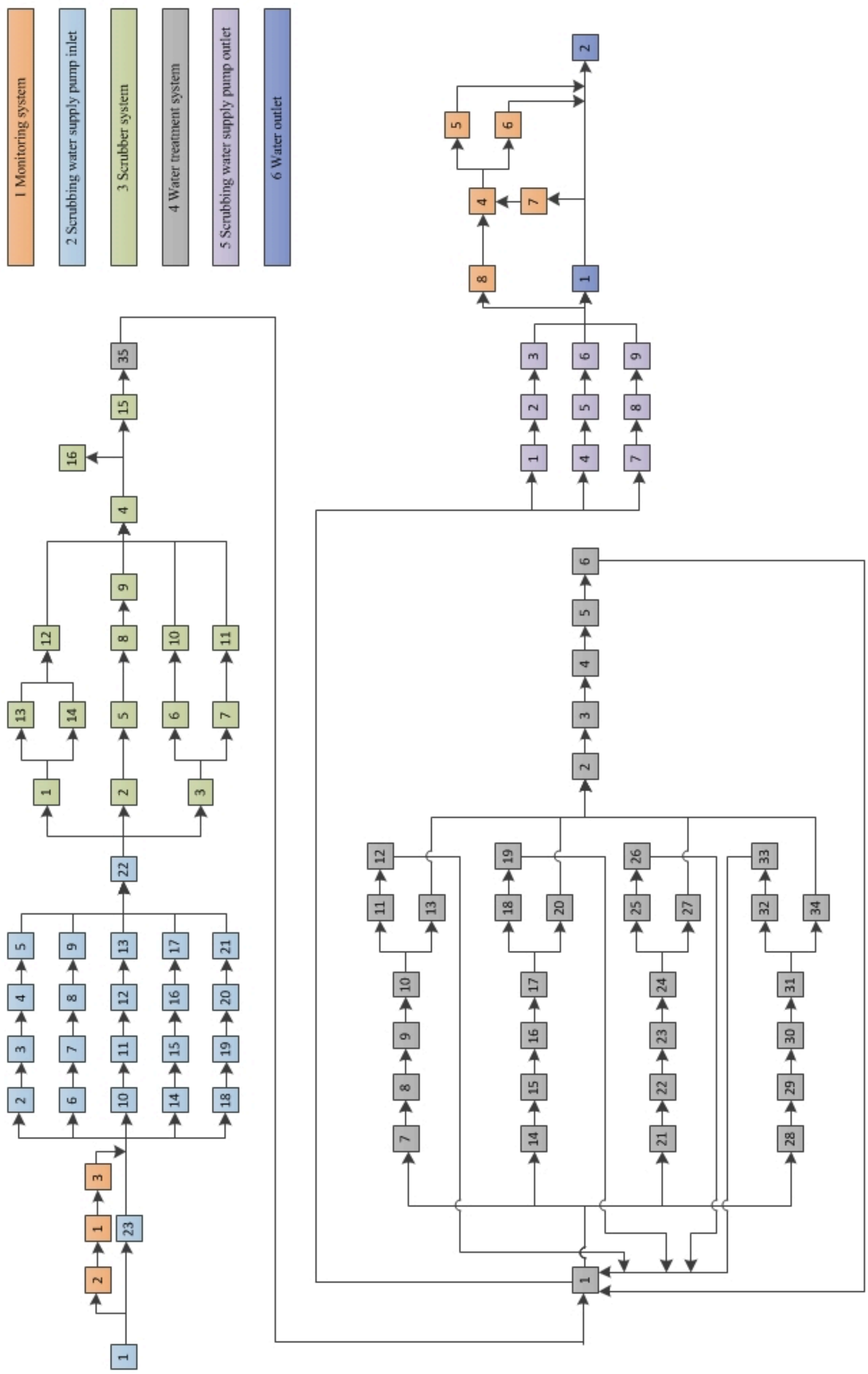


Figure G.1: Schematic block diagram of exhaust gas scrubber system

H. FMECA

FMECA ID	System		Component ID	Component	Component Function
1	1	Monitoring system	1.01	Inlet monitor	Measures water quality
2	1	Monitoring system	1.01	Inlet monitor	Measures water quality
3	1	Monitoring system	1.01	Inlet monitor	Measures water quality
4	1	Monitoring system	1.02	Manual gate valve	Open/close water to inlet monitor
5	1	Monitoring system	1.02	Manual gate valve	Open/close water to inlet monitor
6	1	Monitoring system	1.02	Manual gate valve	Open/close water to inlet monitor
7	1	Monitoring system	1.02	Manual gate valve	Open/close water to inlet monitor
8	1	Monitoring system	1.03	Manual gate valve	Open/close water to scrubber water supply pump inlet
9	1	Monitoring system	1.03	Manual gate valve	Open/close water to scrubber water supply pump inlet
10	1	Monitoring system	1.03	Manual gate valve	Open/close water to scrubber water supply pump inlet
11	1	Monitoring system	1.03	Manual gate valve	Open/close water to scrubber water supply pump inlet
12	1	Monitoring system	1.04	Outlet monitor	Measures water quality
13	1	Monitoring system	1.04	Outlet monitor	Measures water quality
14	2	Monitoring system	2.04	Outlet monitor	Measures water quality
15	1	Monitoring system	1.05 1.06	Manual gate valve	Open/close water to water outlet
16	1	Monitoring system	1.05 1.06	Manual gate valve	Open/close water to water outlet
17	1	Monitoring system	1.05 1.06	Manual gate valve	Open/close water to water outlet
18	1	Monitoring system	1.05 1.06	Manual gate valve	Open/close water to water outlet
19	1	Monitoring system	1.07 1.08	Manual gate valve	Open/close water to outlet monitor
20	1	Monitoring system	1.07 1.08	Manual gate valve	Open/close water to outlet monitor
21	1	Monitoring system	1.07 1.08	Manual gate valve	Open/close water to outlet monitor
22	1	Monitoring system	1.07 1.08	Manual gate valve	Open/close water to outlet monitor
23	2	Scrubbing water supply pump inlet	2.01	Manual gate valve	Open/close seawater onboard
24	2	Scrubbing water supply pump inlet	2.01	Manual gate valve	Open/close seawater onboard
25	2	Scrubbing water supply pump inlet	2.01	Manual gate valve	Open/close seawater onboard
26	2	Scrubbing water supply pump inlet	2.01	Manual gate valve	Open/close seawater onboard
27	2	Scrubbing water supply pump inlet	2.02 2.06 2.10 2.14 2.18	Manual gate valve	Open/close water to pump
28	2	Scrubbing water supply pump inlet	2.02 2.06 2.10 2.14 2.18	Manual gate valve	Open/close water to pump
29	2	Scrubbing water supply pump inlet	2.02 2.06 2.10 2.14 2.18	Manual gate valve	Open/close water to pump
30	2	Scrubbing water supply pump inlet	2.02 2.06 2.10 2.14 2.18	Manual gate valve	Open/close water to pump
31	2	Scrubbing water supply pump inlet	2.03 2.07 2.11 2.15 2.19	Pump	Pump water to the tower
32	2	Scrubbing water supply pump inlet	2.03 2.07 2.11 2.15 2.19	Pump	Pump water to the tower
33	2	Scrubbing water supply pump inlet	2.03 2.07 2.11 2.15 2.19	Pump	Pump water to the tower
34	2	Scrubbing water supply pump inlet	2.03 2.07 2.11 2.15 2.19	Pump	Pump water to the tower
35	2	Scrubbing water supply pump inlet	2.04 2.08 2.12 2.16 2.20	Manual gate valve	Open/close water to tower

Figure H.1: FMECA (Mari Løvald Andresen 2014)

FMECA ID	System		Component ID	Component	Component Function
36	2	Scrubbing water supply pump inlet	2.04 2.08 2.12 2.16 2.20	Manual gate valve	Open/close water to tower
37	2	Scrubbing water supply pump inlet	2.04 2.08 2.12 2.16 2.20	Manual gate valve	Open/close water to tower
38	2	Scrubbing water supply pump inlet	2.04 2.08 2.12 2.16 2.20	Manual gate valve	Open/close water to tower
39	2	Scrubbing water supply pump inlet	2.05 2.09 2.13 2.17 2.21	Check valve	Provide water to the tower
40	2	Scrubbing water supply pump inlet	2.05 2.09 2.13 2.17 2.21	Check valve	Provide water to the tower
41	2	Scrubbing water supply pump inlet	2.05 2.09 2.13 2.17 2.21	Check valve	Provide water to the tower
42	2	Scrubbing water supply pump inlet	2.05 2.09 2.13 2.17 2.21	Check valve	Provide water to the tower
43	2	Scrubbing water supply pump inlet	2.22	Manual gate valve	Open/close water to tower
44	2	Scrubbing water supply pump inlet	2.22	Manual gate valve	Open/close water to tower
45	2	Scrubbing water supply pump inlet	2.22	Manual gate valve	Open/close water to tower
46	2	Scrubbing water supply pump inlet	2.22	Manual gate valve	Open/close water to tower
47	3	Scrubber system	3.01	Control valve	Control and open/close water to the venturi
48	3	Scrubber system	3.01	Control valve	Control and open/close water to the venturi
49	3	Scrubber system	3.01	Control valve	Control and open/close water to the venturi
50	3	Scrubber system	3.01	Control valve	Control and open/close water to the venturi
51	3	Scrubber system	3.01	Control valve	Control and open/close water to the venturi
52	3	Scrubber system	3.02	Control valve	Control and open/close water to the upper section in scrubber device
53	3	Scrubber system	3.02	Control valve	Control and open/close water to the upper section in scrubber device
54	3	Scrubber system	3.02	Control valve	Control and open/close water to the upper section in scrubber device
55	3	Scrubber system	3.02	Control valve	Control and open/close water to the upper section in scrubber device
56	3	Scrubber system	3.02	Control valve	Control and open/close water to the upper section in scrubber device
57	3	Scrubber system	3.03	Control valve	Control and open/close water to the lower section in scrubber device
58	3	Scrubber system	3.03	Control valve	Control and open/close water to the lower section in scrubber device
59	3	Scrubber system	3.03	Control valve	Control and open/close water to the lower section in scrubber device
60	3	Scrubber system	3.03	Control valve	Control and open/close water to the lower section in scrubber device
61	3	Scrubber system	3.03	Control valve	Control and open/close water to the lower section in scrubber device
62	3	Scrubber system	3.04	Scrubber device	Detain scrubbing process
63	3	Scrubber system	3.04	Scrubber device	Detain scrubbing process
64	3	Scrubber system	3.05	Injection nozzle	Disperse water
65	3	Scrubber system	3.05	Injection nozzle	Disperse water
66	3	Scrubber system	3.06	Injection nozzle	Disperse water
67	3	Scrubber system	3.06	Injection nozzle	Disperse water
68	3	Scrubber system	3.07	Injection nozzle	Disperse water
69	3	Scrubber system	3.07	Injection nozzle	Disperse water

FMECA ID	System		Component ID	Component	Component Function
70	3	Scrubber system	3.08	Steam cleaning	Cleans steam in the scrubber device
71	3	Scrubber system	3.09	Droplet separator	Remove water droplets from exhaust gas
72	3	Scrubber system	3.10	Packed bed	Remove particulates from exhaust gas
73	3	Scrubber system	3.11	Packed bed	Remove particulates from exhaust gas
74	3	Scrubber system	3.12	Venturi	Detain scrubbing process
75	3	Scrubber system	3.12	Venturi	Detain scrubbing process
76	3	Scrubber system	3.13	Injection nozzle	Disperse water
77	3	Scrubber system	3.13	Injection nozzle	Disperse water
78	3	Scrubber system	3.14	Injection nozzle	Disperse water
79	3	Scrubber system	3.14	Injection nozzle	Disperse water
80	3	Scrubber system	3.15	Drainpipe	Lead water to the residence tank
81	4	Water treatment system	4.01	Residence tank	Stores effluent
82	4	Water treatment system	4.01	Residence tank	Stores effluent
83	4	Water treatment system	4.02	Sludge tank	Stores disposal of effluent residues
84	4	Water treatment system	4.02	Sludge tank	Stores disposal of effluent residues
85	4	Water treatment system	4.03	Manual gate valve	Open/close water to pump
86	4	Water treatment system	4.03	Manual gate valve	Open/close water to pump
87	4	Water treatment system	4.03	Manual gate valve	Open/close water to pump
88	4	Water treatment system	4.03	Manual gate valve	Open/close water to pump
89	4	Water treatment system	4.04	Pump	Pump water to the residence tank
90	4	Water treatment system	4.04	Pump	Pump water to the residence tank
91	4	Water treatment system	4.04	Pump	Pump water to the residence tank
92	4	Water treatment system	4.04	Pump	Pump water to the residence tank
93	4	Water treatment system	4.05	Manual gate valve	Open/close water to residence tank
94	4	Water treatment system	4.05	Manual gate valve	Open/close water to residence tank
95	4	Water treatment system	4.05	Manual gate valve	Open/close water to residence tank
96	4	Water treatment system	4.05	Manual gate valve	Open/close water to residence tank
97	4	Water treatment system	4.06	Check valve	Provide water to the residence tank
98	4	Water treatment system	4.06	Check valve	Provide water to the residence tank
99	4	Water treatment system	4.06	Check valve	Provide water to the residence tank
100	4	Water treatment system	4.06	Check valve	Provide water to the residence tank
101	4	Water treatment system	4.07 4.14 4.21 4.28	Manual gate valve	Open/close water to pump
102	4	Water treatment system	4.07 4.14 4.21 4.28	Manual gate valve	Open/close water to pump
103	4	Water treatment system	4.07 4.14 4.21 4.28	Manual gate valve	Open/close water to pump

FMECA ID	System		Component ID	Component	Component Function
104	4	Water treatment system	4.07 4.14 4.21 4.28	Manual gate valve	Open/close water to pump
105	4	Water treatment system	4.08 4.15 4.22 4.29	Pump	Pump water to hydrocyclone
106	4	Water treatment system	4.08 4.15 4.22 4.29	Pump	Pump water to hydrocyclone
107	4	Water treatment system	4.08 4.15 4.22 4.29	Pump	Pump water to hydrocyclone
108	4	Water treatment system	4.08 4.15 4.22 4.29	Pump	Pump water to hydrocyclone
109	4	Water treatment system	4.09 4.16 4.23 4.30	Manual gate valve	Open/close water to hydrocyclone
110	4	Water treatment system	4.09 4.16 4.23 4.30	Manual gate valve	Open/close water to hydrocyclone
111	4	Water treatment system	4.09 4.16 4.23 4.30	Manual gate valve	Open/close water to hydrocyclone
112	4	Water treatment system	4.09 4.16 4.23 4.30	Manual gate valve	Open/close water to residence tank
113	4	Water treatment system	4.10 4.17 4.24 4.31	Hydrocyclone	Separate particles from the washwater
114	4	Water treatment system	4.10 4.17 4.24 4.31	Hydrocyclone	Separate particles from the washwater
115	4	Water treatment system	4.11 4.18 4.25 4.32	Manual gate valve	Open/close water to residence tank
116	4	Water treatment system	4.11 4.18 4.25 4.32	Manual gate valve	Open/close water to residence tank
117	4	Water treatment system	4.11 4.18 4.25 4.32	Manual gate valve	Open/close water to residence tank
118	4	Water treatment system	4.11 4.18 4.25 4.32	Manual gate valve	Open/close water to residence tank
119	4	Water treatment system	4.12 4.19 4.26 4.33	Check valve	Provide water to residence tank
120	4	Water treatment system	4.12 4.19 4.26 4.33	Check valve	Provide water to residence tank
121	4	Water treatment system	4.12 4.19 4.26 4.33	Check valve	Provide water to residence tank
122	4	Water treatment system	4.12 4.19 4.26 4.33	Check valve	Provide water to residence tank
123	4	Water treatment system	4.13 4.20 4.27 4.34	Control valve	Control and open/close water to the sludge tank
124	4	Water treatment system	4.13 4.20 4.27 4.34	Control valve	Control and open/close water to the sludge tank
125	4	Water treatment system	4.13 4.20 4.27 4.34	Control valve	Control and open/close water to the sludge tank
126	4	Water treatment system	4.13 4.20 4.27 4.34	Control valve	Control and open/close water to the sludge tank
127	4	Water treatment system	4.13 4.20 4.27 4.34	Control valve	Control and open/close water to the sludge tank
128	4	Water treatment system	4.35	Control valve	Control and open/close water to the residence tank
129	4	Water treatment system	4.35	Control valve	Control and open/close water to the residence tank
130	4	Water treatment system	4.35	Control valve	Control and open/close water to the residence tank
131	4	Water treatment system	4.35	Control valve	Control and open/close water to the residence tank
132	4	Water treatment system	4.35	Control valve	Control and open/close water to the residence tank
133	5	Scrubbing water supply pump outlet	5.01 5.04 5.07	Manual gate valve	Open/close scrubber water to pump
134	5	Scrubbing water supply pump outlet	5.01 5.04 5.07	Manual gate valve	Open/close scrubber water to pump
135	5	Scrubbing water supply pump outlet	5.01 5.04 5.07	Manual gate valve	Open/close scrubber water to pump
136	5	Scrubbing water supply pump outlet	5.01 5.04 5.07	Manual gate valve	Open/close scrubber water to pump
137	5	Scrubbing water supply pump outlet	5.02 5.05 5.08	Pump	Pump water to the outlet

FMECA ID	System		Component ID	Component	Component Function
138	5	Scrubbing water supply pump outlet	5.02 5.05 5.08	Pump	Pump water to the outlet
139	5	Scrubbing water supply pump outlet	5.02 5.05 5.08	Pump	Pump water to the outlet
140	5	Scrubbing water supply pump outlet	5.02 5.05 5.08	Pump	Pump water to the outlet
141	5	Scrubbing water supply pump outlet	5.03 5.06 5.09	Manual gate valve	Open/close scrubber water to outlet
142	5	Scrubbing water supply pump outlet	5.03 5.06 5.09	Manual gate valve	Open/close scrubber water to outlet
143	5	Scrubbing water supply pump outlet	5.03 5.06 5.09	Manual gate valve	Open/close scrubber water to outlet
144	5	Scrubbing water supply pump outlet	5.03 5.06 5.09	Manual gate valve	Open/close scrubber water to outlet
145	6	Water outlet	6.01	Check valve	Provide water to the outlet
146	6	Water outlet	6.01	Check valve	Provide water to the outlet
147	6	Water outlet	6.01	Check valve	Provide water to the outlet
148	6	Water outlet	6.01	Check valve	Provide water to the outlet
149	6	Water outlet	6.02	Control valve	Control and open/close water to outlet
150	6	Water outlet	6.02	Control valve	Control and open/close water to outlet
151	6	Water outlet	6.02	Control valve	Control and open/close water to outlet
152	6	Water outlet	6.02	Control valve	Control and open/close water to outlet
153	6	Water outlet	6.02	Control valve	Control and open/close water to outlet

FMECA ID	Failure Mode	Failure Cause
1	Fail to function on demand	Electronic failure, sensing element, blockage/plugged, faulty signal, instrument failure, no signal
2	Abnormal output	Sensing element, out of adjustment
3	Spurious operation	Electronic failure, sensing element, blockage/plugged, faulty signal, instrument failure, no signal
4	Plugged/choked	Corrosion, fouling
5	External leakage	Corrosion, leakage, looseness, material failure, mechanical failure
6	Fail to close on demand	Blockage/plugged, instrument failure, mechanical failure
7	Fail to open on demand	Blockage/plugged, corrosion, deformation, instrument, mechanical, wear
8	Plugged/choked	Corrosion, fouling
9	External leakage	Corrosion, leakage, looseness, material failure, mechanical failure
10	Fail to close on demand	Blockage/plugged, instrument failure, mechanical failure
11	Fail to open on demand	Blockage/plugged, corrosion, deformation, instrument, mechanical, wear
12	Fail to function on demand	Electronic failure, sensing element, blockage/plugged, faulty signal, instrument failure, no signal
13	Abnormal output	Sensing element, out of adjustment
14	Spurious operation	Electronic failure, sensing element, blockage/plugged, faulty signal, instrument failure, no signal
15	Plugged/choked	Corrosion, fouling
16	External leakage	Corrosion, leakage, looseness, material failure, mechanical failure
17	Fail to close on demand	Blockage/plugged, instrument failure, mechanical failure
18	Fail to open on demand	Blockage/plugged, corrosion, deformation, instrument, mechanical, wear
19	Plugged/choked	Corrosion, fouling
20	External leakage	Corrosion, leakage, looseness, material failure, mechanical failure
21	Fail to close on demand	Blockage/plugged, instrument failure, mechanical failure
22	Fail to open on demand	Blockage/plugged, corrosion, deformation, instrument, mechanical, wear
23	Plugged/choked	Corrosion, fouling
24	External leakage	Corrosion, leakage, looseness, material failure, mechanical failure
25	Fail to close on demand	Blockage/plugged, instrument failure, mechanical failure
26	Fail to open on demand	Blockage/plugged, corrosion, deformation, instrument, mechanical, wear
27	Plugged/choked	Corrosion, fouling
28	External leakage	Corrosion, leakage, looseness, material failure, mechanical failure
29	Fail to close on demand	Blockage/plugged, instrument failure, mechanical failure
30	Fail to open on demand	Blockage/plugged, corrosion, deformation, instrument, mechanical, wear
31	Spurious stop	Control unit, instrument, pressure, temperature, monitoring, seals
32	External leakage	Bearing, casing, filters, oil, seals
33	Fail to start on demand	Control unit, instrument, thrust bearing
34	Vibration	Impeller, vibrations, radial bearing
35	Plugged/choked	Corrosion, fouling

FMECA ID	Failure Mode	Failure Cause
36	External leakage	Corrosion, leakage, looseness, material failure, mechanical failure
37	Fail to close on demand	Blockage/plugged, instrument failure, mechanical failure
38	Fail to open on demand	Blockage/plugged, corrosion, deformation, instrument, mechanical, wear
39	Plugged/choked	Corrosion, fouling
40	External leakage	Corrosion, leakage, looseness, material failure, mechanical failure
41	Fail to close on demand	Blockage/plugged, instrument failure, mechanical failure
42	Fail to open on demand	Blockage/plugged, corrosion, deformation, instrument, mechanical, wear
43	Plugged/choked	Corrosion, fouling
44	External leakage	Corrosion, leakage, looseness, material failure, mechanical failure
45	Fail to close on demand	Blockage/plugged, instrument failure, mechanical failure
46	Fail to open on demand	Blockage/plugged, corrosion, deformation, instrument, mechanical, wear
47	Plugged/choked	Corrosion, fouling
48	External leakage	Corrosion, leakage, looseness, material failure, mechanical failure
49	Fail to close on demand	Blockage/plugged, instrument failure, mechanical failure
50	Fail to control	Blockage/plugged, control failure, corrosion, deformation, instrument, mechanical, wear
51	Fail to open on demand	Blockage/plugged, control failure, corrosion, deformation, instrument, mechanical, wear
52	Plugged/choked	Corrosion, fouling
53	External leakage	Corrosion, leakage, looseness, material failure, mechanical failure
54	Fail to close on demand	Blockage/plugged, instrument failure, mechanical failure
55	Fail to control	Blockage/plugged, control failure, corrosion, deformation, instrument, mechanical, wear
56	Fail to open on demand	Blockage/plugged, control failure, corrosion, deformation, instrument, mechanical, wear
57	Plugged/choked	Corrosion, fouling
58	External leakage	Corrosion, leakage, looseness, material failure, mechanical failure
59	Fail to close on demand	Blockage/plugged, instrument failure, mechanical failure
60	Fail to control	Blockage/plugged, control failure, corrosion, deformation, instrument, mechanical, wear
61	Fail to open on demand	Blockage/plugged, control failure, corrosion, deformation, instrument, mechanical, wear
62	External leakage	Corrosion, high pressures
63	Structural deficiency	Body/shell, support
64	Plugged/choked	Corrosion, fouling, wear
65	Fall down	Corrosion, fouling, high pressures, looseness, wear
66	Plugged/choked	Corrosion, fouling, wear
67	Fall down	Corrosion, fouling, high pressures, looseness, wear
68	Plugged/choked	Corrosion, fouling, wear
69	Fall down	Corrosion, fouling, high pressures, looseness, wear

FMECA ID	Failure Mode	Failure Cause
70	Plugged/choked	Corrosion, fouling, wear
71	Plugged/choked	Corrosion, fouling, wear, bad cleaning, too many deposits
72	Plugged/choked	Corrosion, fouling, wear, debris, too large particulate
73	Plugged/choked	Corrosion, fouling, wear, debris, too large particulate
74	External leakage	Corrosion, high pressures
75	Structural deficiency	Body/shell, support
76	Plugged/choked	Corrosion, fouling, wear
77	Fall down	Corrosion, fouling, high pressures, looseness, wear
78	Plugged/choked	Corrosion, fouling, wear
79	Fall down	Corrosion, fouling, high pressures, looseness, wear
80	Plugged/choked	Falling of nozzles, downstream valve closed
81	Structural deficiency	Corrosion, lack of maintenance
82	External leakage	Corrosion, lack of maintenance
83	Structural deficiency	Corrosion, lack of maintenance
84	External leakage	Corrosion, lack of maintenance
85	Plugged/choked	Corrosion, fouling
86	External leakage	Corrosion, leakage, looseness, material failure, mechanical failure
87	Fail to close on demand	Blockage/plugged, instrument failure, mechanical failure
88	Fail to open on demand	Blockage/plugged, corrosion, deformation, instrument, mechanical, wear
89	Spurious stop	Control unit, instrument, pressure, temperature, monitoring, seals
90	External leakage	Bearing, casing, filters, oil, seals
91	Fail to start on demand	Control unit, instrument, thrust bearing
92	Vibration	Impeller, vibrations, radial bearing
93	Plugged/choked	Corrosion, fouling
94	External leakage	Corrosion, leakage, looseness, material failure, mechanical failure
95	Fail to close on demand	Blockage/plugged, instrument failure, mechanical failure
96	Fail to open on demand	Blockage/plugged, corrosion, deformation, instrument, mechanical, wear
97	Plugged/choked	Corrosion, fouling
98	External leakage	Corrosion, leakage, looseness, material failure, mechanical failure
99	Fail to close on demand	Blockage/plugged, instrument failure, mechanical failure
100	Fail to open on demand	Blockage/plugged, corrosion, deformation, instrument, mechanical, wear
101	Plugged/choked	Corrosion, fouling
102	External leakage	Corrosion, leakage, looseness, material failure, mechanical failure
103	Fail to close on demand	Blockage/plugged, instrument failure, mechanical failure

FMECA ID	Failure Mode	Failure Cause
104	Fail to open on demand	Blockage/plugged, corrosion, deformation, instrument, mechanical, wear
105	Spurious stop	Control unit, instrument, pressure, temperature, monitoring, seals
106	External leakage	Bearing, casing, filters, oil, seals
107	Fail to start on demand	Control unit, instrument, thrust bearing
108	Vibration	Impeller, vibrations, radial bearing
109	Plugged/choked	Corrosion, fouling
110	External leakage	Corrosion, leakage, looseness, material failure, mechanical failure
111	Fail to close on demand	Blockage/plugged, instrument failure, mechanical failure
112	Fail to open on demand	Blockage/plugged, corrosion, deformation, instrument, mechanical, wear
113	Plugged/choked	Corrosion, fouling, wear
114	Structural deficiency	Corrosion, strains, wear
115	Plugged/choked	Corrosion, fouling
116	External leakage	Corrosion, leakage, looseness, material failure, mechanical failure
117	Fail to close on demand	Blockage/plugged, instrument failure, mechanical failure
118	Fail to open on demand	Blockage/plugged, corrosion, deformation, instrument, mechanical, wear
119	Plugged/choked	Corrosion, fouling
120	External leakage	Corrosion, leakage, looseness, material failure, mechanical failure
121	Fail to close on demand	Blockage/plugged, instrument failure, mechanical failure
122	Fail to open on demand	Blockage/plugged, corrosion, deformation, instrument, mechanical, wear
123	Plugged/choked	Corrosion, fouling
124	External leakage	Corrosion, leakage, looseness, material failure, mechanical failure
125	Fail to close on demand	Blockage/plugged, instrument failure, mechanical failure
126	Fail to control	Blockage/plugged, control failure, corrosion, deformation, instrument, mechanical, wear
127	Fail to open on demand	Blockage/plugged, control failure, corrosion, deformation, instrument, mechanical, wear
128	Plugged/choked	Corrosion, fouling
129	External leakage	Corrosion, leakage, looseness, material failure, mechanical failure
130	Fail to close on demand	Blockage/plugged, instrument failure, mechanical failure
131	Fail to control	Blockage/plugged, control failure, corrosion, deformation, instrument, mechanical, wear
132	Fail to open on demand	Blockage/plugged, control failure, corrosion, deformation, instrument, mechanical, wear
133	Plugged/choked	Corrosion, fouling
134	External leakage	Corrosion, leakage, looseness, material failure, mechanical failure
135	Fail to close on demand	Blockage/plugged, instrument failure, mechanical failure
136	Fail to open on demand	Blockage/plugged, corrosion, deformation, instrument, mechanical, wear
137	Spurious stop	Control unit, instrument, pressure, temperature, monitoring, seals

FMECA ID	Failure Mode	Failure Cause
138	External leakage	Bearing, casing, filters, oil, seals
139	Fail to start on demand	Control unit, instrument, thrust bearing
140	Vibration	Impeller, vibrations, radial bearing
141	Plugged/choked	Corrosion, fouling
142	External leakage	Corrosion, leakage, looseness, material failure, mechanical failure
143	Fail to close on demand	Blockage/plugged, instrument failure, mechanical failure
144	Fail to open on demand	Blockage/plugged, corrosion, deformation, instrument, mechanical, wear
145	Plugged/choked	Corrosion, fouling
146	External leakage	Corrosion, leakage, looseness, material failure, mechanical failure
147	Fail to close on demand	Blockage/plugged, instrument failure, mechanical failure
148	Fail to open on demand	Blockage/plugged, corrosion, deformation, instrument, mechanical, wear
149	Plugged/choked	Corrosion, fouling
150	External leakage	Corrosion, leakage, looseness, material failure, mechanical failure
151	Fail to close on demand	Blockage/plugged, instrument failure, mechanical failure
152	Fail to control	Blockage/plugged, control failure, corrosion, deformation, instrument, mechanical, wear
153	Fail to open on demand	Blockage/plugged, control failure, corrosion, deformation, instrument, mechanical, wear

FMECA ID	Local Failure Effect	Global Failure Effect
1	pH, PAH, turbidity and temperature not recorded	Out of compliance
2	pH, PAH, turbidity and temperature measures are wrong	Can not demostrate compliance
3	pH, PAH, turbidity and temperature measures are wrong	Can not demostrate compliance
4	Lowered flow of water, water is not monitored and is led directly to scrubbing water supply pump inlet	Potential out of compliance
5	Water is not monitored, water released to ambient space	Potential out of compliance
6	Water entering the monitoring system	Can not perform maintenance
7	Water is not monitored and is led directly to scrubbing water supply pump inlet	Potential out of compliance
8	Lowered flow of water, stagnateing water in inlet monitor, wrong reading	Can not demostrate compliance
9	Water released to ambient space	Leakage of water onboard
10	Water entering the monitoring system	Can not perform maintenance
11	Blockage in inlet monitor, stagnathing water, wrong reading	Potential out of compliance
12	pH, PAH, turbidity and temperature not recorded	Out of compliance
13	pH, PAH, turbidity and temperature measures are wrong	Can not demostrate compliance
14	pH, PAH, turbidity and temperature measures are wrong	Can not demostrate compliance
15	Lowered flow of water, water is not led to water outlet, blockage in outlet monitor	Can not demostrate compliance
16	Water released to ambient space	Leakage of water onboard
17	Water is led spontaneously out from outlet monitor	Can not perform maintenance
18	Blockage in oulet monitor	Potential out of compliance
19	Lowered flow of water, water is not monitored and is led directly to water outlet	Potential out of compliance
20	Water is not monitored, water released to ambient space	Potential out of compliance
21	Water entering the monitoring system	Can not perform maintenance
22	Water is not monitored and is led directly to water outlet	Potential out of compliance
23	Lowered flow of water, water is not injected om bord	Out of compliance
24	Water released to ambient space	Leakage of water onboard
25	Water is led spontaneously onboard	Potential out of compliance
26	No water is injected onboard	Out of compliance
27	Lowered flow of water, water don´t access the pump	Can not demostrate compliance
28	Water released to ambient space	Leakage of water onboard
29	Water is led spontaneously to pump	Can not perform maintenance
30	Water don´t access the pump	Potential out of compliance
31	Loss of pressure to reach tower, no water pumped to tower	Potential out of compliance
32	Water released to ambient space	Leakage of water onboard
33	No water pumped to tower	Out of compliance
34	Insufficient suction pressure, air in water	Out of compliance
35	Lowered flow of water, water don´t access the tower, too high backpressure	Can not demostrate compliance

FMECA ID	Local Failure Effect	Global Failure Effect
36	Water released to ambient space	Leakage of water onboard
37	Water is led spontaneously through	Can not perform maintenance
38	Water don´t access the tower, too high backpressure	Potential out of compliance
39	Lowered flow of water, water don´t access the tower, too high backpressure	Can not demostrate compliance
40	Water released to ambient space	Leakage of water onboard
41	Water is led spontaneously through	Potential out of compliance
42	Water don´t access the tower, too high backpressure	Potential out of compliance
43	Lowered flow of water, water don´t access the tower	Out of compliance
44	Water released to ambient space	Leakage of water onboard
45	Water is led spontaneously through	Potential out of compliance
46	Water don´t access the tower	Out of compliance
47	Lowered flow of water, lowered spraying effciency from nozzle 3,13 and 3,14, water don´t access the nozzles	Out of compliance
48	Water released to ambient space, lowered flow of water to nozzles	Leakage of water onboard
49	Water is led spontaneously through the valve	Can not perform maintenance
50	Wrong amount of water flow through the valve	Potential out of compliance
51	Water don´t access the venturi	Out of compliance
52	Lowered flow of water, lowered spraying effciency from nozzle 3,5, water don´t access the nozzle	Out of compliance
53	Water released to ambient space, lowered flow of water to nozzle	Leakage of water onboard
54	Water is led spontaneously through the valve	Can not perform maintenance
55	Wrong amount of water flow through the valve	Potential out of compliance
56	Water don´t access the scrubber device	Out of compliance
57	Lowered flow of water, lowered spraying effciency from nozzle 3,6 and 3,7, water don´t access the nozzles	Out of compliance
58	Water released to ambient space, lowered flow of water to nozzles	Leakage of water onboard
59	Water is led spontaneously through the valve	Can not perform maintenance
60	Wrong amount of water flow through the valve	Potential out of compliance
61	Water don´t access the scrubber device	Out of compliance
62	Exhaust and water released to ambient space	Leakage of water onboard, out of compliance
63	Exhaust and water released to ambient space	Leakage of water onboard, out of compliance
64	Lowered spraying efficiency	Potentially out of compliance

FMECA ID	Local Failure Effect	Global Failure Effect
65	No water dispersion	Potentially out of compliance, damage or block valves or piping downstream
66	Lowered spraying efficiency	Potentially out of compliance
67	No water dispersion	Potentially out of compliance, damage or block valves or piping downstream
68	Lowered spraying efficiency	Potentially out of compliance
69	No water dispersion	Potentially out of compliance, damage or block valves or piping downstream
70	Too high backpressure	Potential out of compliance
71	Too high backpressure	Potential out of compliance
72	Too high backpressure	Potential out of compliance
73	Too high backpressure	Potential out of compliance
74	Exhaust and water released to ambient space	Leakage of water onboard
75	Exhaust and water released to ambient space	Leakage of water onboard
76	Lowered spraying efficiency, potentially out of compliance	Potentially out of compliance
77	Lowered spraying efficiency, potentially out of compliance. Damage or block valves or piping downstream	Potentially out of compliance, damage or block valves or piping downstream
78	Lowered spraying efficiency, potentially out of compliance	Potentially out of compliance
79	Lowered spraying efficiency, potentially out of compliance. Damage or block valves or piping downstream	Potentially out of compliance, damage or block valves or piping downstream
80	Flooding of tower	Too high backpressure on the engine, stability issues
81	Water released to ambient space	Leakage of acidic water onboard
82	Water released to ambient space	Leakage of acidic water onboard
83	Water released to ambient space	Leakage of water onboard
84	Water released to ambient space	Leakage of water onboard
85	Lowered flow of water, water don´t access the pump	Can not demostrate compliance
86	Water released to ambient space	Leakage of water onboard
87	Water is led spontaneously to pump	Can not perform maintenance
88	Water don´t access the pump	Potential out of compliance
89	Loss of pressure to residaul tank, no water pumped to residence tank	Potential out of compliance
90	Water released to ambient space	Leakage of water onboard
91	No water pumped to residence tank	Out of compliance
92	Insufficient suction pressure, air in water	Out of compliance
93	Lowered flow of water, water don´t access residence tank, too high backpressure	Can not demostrate compliance
94	Water released to ambient space	Leakage of water onboard

FMECA ID	Local Failure Effect	Global Failure Effect
95	Water is led spontaneously through the valve	Can not perform maintenance
96	Water don´t access the residence tank, too high backpressure	Potential out of compliance
97	Lowered flow of water, water don´t access the residence tank, too high backpressure	Can not demostrate compliance
98	Water released to ambient space	Leakage of water onboard
99	Water is led spontaneously through the valve	Potential out of compliance
100	Water don´t access the residence tank, too high backpressure	Potential out of compliance
101	Lowered flow of water, water don´t access the hydrocyclone	Can not demostrate compliance
102	Water released to ambient space, lowered flow of water	Leakage of water onboard
103	Water is led spontaneously to pump	Can not perform maintenance
104	Water don´t access the pump	Potential out of compliance
105	Loss of pressure to hydrocyclone, no water pumped to hydrocyclone	Potential out of compliance
106	Water released to ambient space	Leakage of water onboard
107	No water pumped to residence tank	Out of compliance
108	Insufficient suction pressure, air in water	Out of compliance
109	Lowered flow of water, water don´t access residence tank, too high backpressure	Can not demostrate compliance
110	Water released to ambient space	Leakage of water onboard
111	Water is led spontaneously through the valve	Can not perform maintenance
112	Water don´t access the residence tank, too high backpressure	Potential out of compliance
113	Lowered flow of water, uncleaned water led to residence tank/sludge tank	Potential out of compliance
114	Lowered flow of water, water released to ambient space	Leakage of water onboard
115	Lowered flow of water, backpressure	Potential out of compliance
116	Water released to ambient space	Leakage of water onboard
117	Water is led spontaneously out from hydrocyclone	Can not perform maintenance
118	Backpressure	Potentially out of compliance
119	Lowered flow of water, water don´t access the residence tank, backpressure	Can not demostrate compliance
120	Water released to ambient space	Leakage of water onboard
121	Water is led spontaneously through the valve	Potential out of compliance
122	Water don´t access the residence tanke, backpressure	Potential out of compliance
123	Lowered flow of water, water don´t access the sludge tank	Potential out of compliance
124	Water released to ambient space, lowered flow of water to sludge tank	Leakage of water onboard
125	Water is led spontaneously through the valve, pressure loss in hydrocyclone	Can not perform maintenance
126	Wrong amount of water flow through the valve, pressure loss in the hydrocyclone	Potential out of compliance
127	Water don´t access the sludge tank, backpressure	Out of compliance
128	Lowered flow of water, water don´t access the residence tank	Potential out of compliance

FMECA ID	Local Failure Effect	Global Failure Effect
129	Water released to ambient space, lowered flow of water to residence tank	Leakage of water onboard
130	Water is led spontaneously through the valve, pressure loss in tower, flooding of residence tank	Can not perform maintenance
131	Wrong amount of water flow through the valve, pressure loss in tower, flooding of residence tank	Potential out of compliance
132	Water don´t access the residence tank, backpressure	Out of compliance
133	Lowered flow of water, water don´t access pump	Can not demostrate compliance
134	Water released to ambient space, lowered flow of water	Leakage of water onboard
135	Water is led spontaneously to pump	Can not perform maintenance
136	Water don´t access the pump	Potential out of compliance
137	Lowered pressure to water outlet, no water pumped to water outlet	Potential out of compliance
138	Water released to ambient space	Leakage of water onboard
139	No water pumped to water outlet	Out of compliance
140	Insufficient suction pressure, air in water	Out of compliance
141	Lowered flow of water, water don´t access, too high backpressure	Can not demostrate compliance
142	Water released to ambient space	Leakage of water onboard
143	Water is led spontaneously through the valve	Can not perform maintenance
144	Water don´t access through, too high backpressure	Potential out of compliance
145	Lowered flow of water, water don´t access, backpressure	Can not demostrate compliance
146	Water released to ambient space	Leakage of water onboard
147	Water is led spontaneously through the valve	Potential out of compliance
148	Water don´t flow through the valve, backpressure	Potential out of compliance
149	Lowered flow of water, water don´t flow though the valve	Potential out of compliance
150	Water released to ambient space, lowered flow of water	Leakage of water onboard
151	Water is led spontaneously to the sea	Can not perform maintenance
152	Wrong amount of water flow through the valve	Potential out of compliance
153	No discharge of water, backpressure	Out of compliance

FMECA ID	Failure Detection	"Existing Safeguard"
1	Exhaust gas monitoring	Software update frequently, Calibration
2	Exhaust gas monitoring	Software update frequently, Calibration
3	Exhaust gas monitoring	Software update frequently, Calibration
4	Exhaust gas monitoring, cleaning initiated, inspection	Cleaning frequently
5	Exhaust gas monitoring, inspection	Calibration frequently
6	Exhaust gas monitoring, inspection	Calibration and cleaning frequently
7	Exhaust gas monitoring, inspection	Calibration and cleaning frequently
8	Exhaust gas monitoring, cleaning initiated, inspection	Cleaning frequently
9	Exhaust gas monitoring, inspection	Calibration frequently
10	Exhaust gas monitoring, inspection	Calibration and cleaning frequently
11	Exhaust gas monitoring, inspection	Calibration and cleaning frequently
12	Exhaust gas monitoring	Software update frequently, Calibration
13	Exhaust gas monitoring	Software update frequently, Calibration
14	Exhaust gas monitoring	Software update frequently, Calibration
15	Exhaust gas monitoring, cleaning initiated, inspection	Cleaning frequently, redundancy
16	Exhaust gas monitoring, inspection	Calibration frequently, redundancy
17	Exhaust gas monitoring, inspection	Calibration and cleaning frequently, redundancy
18	Exhaust gas monitoring, inspection	Calibration and cleaning frequently, redundancy
19	Exhaust gas monitoring, cleaning initiated, inspection	Cleaning frequently, redundancy
20	Exhaust gas monitoring, inspection	Calibration frequently, redundancy
21	Exhaust gas monitoring, inspection	Calibration and cleaning frequently, redundancy
22	Exhaust gas monitoring, inspection	Calibration and cleaning frequently, redundancy
23	Exhaust gas monitoring, cleaning initiated, inspection	Cleaning frequently
24	Exhaust gas monitoring, inspection	Calibration frequently
25	Exhaust gas monitoring, inspection	Calibration and cleaning frequently
26	Exhaust gas monitoring, inspection	Calibration and cleaning frequently
27	Exhaust gas monitoring, cleaning initiated, inspection	Cleaning frequently, redundancy
28	Exhaust gas monitoring, inspection	Calibration frequently, redundancy
29	Exhaust gas monitoring, inspection	Calibration and cleaning frequently, redundancy
30	Exhaust gas monitoring, inspection	Calibration and cleaning frequently, redundancy
31	Exhaust gas monitoring	Calibration and frequency analysis frequently, redundancy
32	Exhaust gas monitoring, inspection	Calibration and frequency analysis frequently, redundancy
33	Exhaust gas monitoring	Calibration and frequency analysis frequently, redundancy
34	Exhaust gas monitoring, strain gauge	Calibration and frequency analysis frequently, redundancy

FMECA ID	Failure Detection	"Existing Safeguard"
35	Exhaust gas monitoring, cleaning initiated, inspection	Cleaning frequently, redundancy
36	Exhaust gas monitoring, inspection	Calibration frequently, redundancy
37	Exhaust gas monitoring, inspection	Calibration and cleaning frequently, redundancy
38	Exhaust gas monitoring, inspection	Calibration and cleaning frequently, redundancy
39	Exhaust gas monitoring, cleaning initiated, inspection	Cleaning frequently, redundancy
40	Exhaust gas monitoring, inspection	Calibration frequently, redundancy
41	Exhaust gas monitoring, inspection	Calibration and cleaning frequently, redundancy
42	Exhaust gas monitoring, inspection, backpressure	Calibration and cleaning frequently, redundancy
43	Exhaust gas monitoring, cleaning initiated, inspection	Cleaning frequently
44	Exhaust gas monitoring, inspection	Calibration frequently
45	Exhaust gas monitoring, inspection	Calibration and cleaning frequently
46	Exhaust gas monitoring, inspection	Calibration and cleaning frequently
47	Exhaust gas monitoring, cleaning initiated	Cleaning frequently
48	Exhaust gas monitoring	Calibration frequently
49	Exhaust gas monitoring	Calibration and cleaning frequently
50	Exhaust gas monitoring	Calibration and cleaning frequently
51	Exhaust gas monitoring	Calibration and cleaning frequently
52	Exhaust gas monitoring, cleaning initiated	Cleaning frequently
53	Exhaust gas monitoring	Calibration frequently
54	Exhaust gas monitoring	Calibration and cleaning frequently
55	Exhaust gas monitoring	Calibration and cleaning frequently
56	Exhaust gas monitoring	Calibration and cleaning frequently
57	Exhaust gas monitoring, cleaning initiated	Cleaning frequently
58	Exhaust gas monitoring	Calibration frequently
59	Exhaust gas monitoring	Calibration and cleaning frequently
60	Exhaust gas monitoring	Calibration and cleaning frequently
61	Exhaust gas monitoring	Calibration and cleaning frequently
62	Inspection	Welding and assembly instructions
63	Inspection	Welding and assembly instructions
64	The exhaust monitoring system will detect the non-compliance, water flow is smaller, cleaning initiated	Cleaning frequently
65	Less water in scrubber device, blockage of drainpipe	Nozzle fixing
66	The exhaust monitoring system will detect the non-compliance, water flow is smaller, cleaning initiated	Cleaning frequently
67	Less water in scrubber device, blockage of drainpipe	Nozzle fixing
68	The exhaust monitoring system will detect the non-compliance, water flow is smaller, cleaning initiated	Cleaning frequently

FMECA ID	Failure Detection	"Existing Safeguard"
69	Less water in scrubber device, blockage of drainpipe	Nozzle fixing
70	Cleaning initiated	Cleaning frequently
71	Cleaning initiated	Cleaning frequently
72	Exhaust will bypass the scrubber, Increased energy consumption	Water flow should keep the packing bed clean
73	Exhaust will bypass the scrubber, Increased energy consumption	Water flow should keep the packing bed clean
74	Inspection	Welding and assembly instructions
75	Inspection	Welding and assembly instructions
76	Less water in scrubber device, cleaning initiated	Cleaning frequently
77	Less water in scrubber device, blockage of drainpipe	Nozzle fixing
78	Less water in scrubber device, cleaning initiated	Cleaning frequently
79	Less water in scrubber device, blockage of drainpipe	Nozzle fixing
80	Cleaning initiated, no water leaving scrubber device	Cleaning frequently
81	Inspection	Welding and assembly instructions
82	Inspection, increased water consumption	Welding and assembly instructions
83	Inspection	Welding and assembly instructions
84	Inspection, increased water consumption	Welding and assembly instructions
85	Exhaust gas monitoring, cleaning initiated, inspection	Cleaning frequently
86	Exhaust gas monitoring, inspection	Calibration frequently
87	Exhaust gas monitoring, inspection	Calibration and cleaning frequently
88	Exhaust gas monitoring, inspection	Calibration and cleaning frequently
89	Exhaust gas monitoring	Calibration and frequency analysis frequently
90	Exhaust gas monitoring, inspection	Calibration and frequency analysis frequently
91	Exhaust gas monitoring	Calibration and frequency analysis frequently
92	Exhaust gas monitoring, strain gauge	Calibration and frequency analysis frequently
93	Exhaust gas monitoring, cleaning initiated, inspection	Cleaning frequently
94	Exhaust gas monitoring, inspection	Calibration frequently
95	Exhaust gas monitoring, inspection	Calibration and cleaning frequently
96	Exhaust gas monitoring, inspection	Calibration and cleaning frequently
97	Exhaust gas monitoring, cleaning initiated, inspection	Cleaning frequently
98	Exhaust gas monitoring, inspection	Calibration frequently
99	Exhaust gas monitoring, inspection	Calibration and cleaning frequently
100	Exhaust gas monitoring, inspection, backpressure	Calibration and cleaning frequently
101	Exhaust gas monitoring, cleaning initiated, inspection	Cleaning frequently, redundancy
102	Exhaust gas monitoring, inspection	Calibration frequently, redundancy

FMECA ID	Failure Detection	"Existing Safeguard"
103	Exhaust gas monitoring, inspection	Calibration and cleaning frequently, redundancy
104	Exhaust gas monitoring, inspection	Calibration and cleaning frequently, redundancy
105	Exhaust gas monitoring	Calibration and frequency analysis frequently, redundancy
106	Exhaust gas monitoring, inspection	Calibration and frequency analysis frequently, redundancy
107	Exhaust gas monitoring	Calibration and frequency analysis frequently, redundancy
108	Exhaust gas monitoring, strain gauge	Calibration and frequency analysis frequently, redundancy
109	Exhaust gas monitoring, cleaning initiated, inspection	Cleaning frequently, redundancy
110	Exhaust gas monitoring, inspection	Calibration frequently, redundancy
111	Exhaust gas monitoring, inspection	Calibration and cleaning frequently, redundancy
112	Exhaust gas monitoring, inspection	Calibration and cleaning frequently, redundancy
113	Cleaning initiated	Cleaning frequently, redundancy
114	Cleaning initiated, ijnspection, reduced capacity	Welding and assembly instructions, redundancy
115	Exhaust gas monitoring, cleaning initiated, inspection	Cleaning frequently, redundancy
116	Exhaust gas monitoring, inspection	Calibration frequently, redundancy
117	Exhaust gas monitoring, inspection	Calibration and cleaning frequently, redundancy
118	Exhaust gas monitoring, inspection	Calibration and cleaning frequently, redundancy
119	Exhaust gas monitoring, cleaning initiated, inspection	Cleaning frequently, redundancy
120	Exhaust gas monitoring, inspection	Calibration frequently, redundancy
121	Exhaust gas monitoring, inspection	Calibration and cleaning frequently, redundancy
122	Exhaust gas monitoring, inspection, backpressure	Calibration and cleaning frequently, redundancy
123	Exhaust gas monitoring, cleaning initiated	Cleaning frequently, redundancy
124	Exhaust gas monitoring	Calibration frequently, redundancy
125	Exhaust gas monitoring	Calibration and cleaning frequently, redundancy
126	Exhaust gas monitoring	Calibration and cleaning frequently, redundancy
127	Exhaust gas monitoring	Calibration and cleaning frequently, redundancy
128	Exhaust gas monitoring, cleaning initiated	Cleaning frequently
129	Exhaust gas monitoring	Calibration frequently
130	Exhaust gas monitoring	Calibration and cleaning frequently
131	Exhaust gas monitoring	Calibration and cleaning frequently
132	Exhaust gas monitoring	Calibration and cleaning frequently

FMECA ID	Failure Detection	"Existing Safeguard"
133	Exhaust gas monitoring, cleaning initiated, inspection	Cleaning frequently, redundancy
134	Exhaust gas monitoring, inspection	Calibration frequently, redundancy
135	Exhaust gas monitoring, inspection	Calibration and cleaning frequently, redundancy
136	Exhaust gas monitoring, inspection	Calibration and cleaning frequently, redundancy
137	Exhaust gas monitoring	Calibration and frequency analysis frequently, redundancy
138	Exhaust gas monitoring, inspection	Calibration and frequency analysis frequently, redundancy
139	Exhaust gas monitoring	Calibration and frequency analysis frequently, redundancy
140	Exhaust gas monitoring, strain gauge	Calibration and frequency analysis frequently, redundancy
141	Exhaust gas monitoring, cleaning initiated, inspection	Cleaning frequently, redundancy
142	Exhaust gas monitoring, inspection	Calibration frequently, redundancy
143	Exhaust gas monitoring, inspection	Calibration and cleaning frequently, redundancy
144	Exhaust gas monitoring, inspection	Calibration and cleaning frequently, redundancy
145	Exhaust gas monitoring, cleaning initiated, inspection	Cleaning frequently
146	Exhaust gas monitoring, inspection	Calibration frequently
147	Exhaust gas monitoring, inspection	Calibration and cleaning frequently
148	Exhaust gas monitoring, inspection, backpressure	Calibration and cleaning frequently
149	Exhaust gas monitoring, cleaning initiated	Cleaning frequently
150	Exhaust gas monitoring	Calibration frequently
151	Exhaust gas monitoring	Calibration and cleaning frequently
152	Exhaust gas monitoring	Calibration and cleaning frequently
153	Exhaust gas monitoring	Calibration and cleaning frequently

FMECA ID	Consequence	Probability	Criticality		Action Items
1	3	3	6	M	Shorter interval between preventive maintenance
2	2	3	5	L	
3	2	3	5	L	
4	3	3	6	M	Ensure proper cleaning, shorter interval btw. preventive maintenance
5	3	2	5	L	
6	1	3	4	L	
7	3	3	6	M	Shorter interval between preventive maintenance
8	3	3	6	M	Ensure proper cleaning, shorter interval btw. preventive maintenance
9	2	2	4	L	
10	2	3	5	L	
11	3	3	6	M	Shorter interval between preventive maintenance
12	3	3	6	M	Shorter interval between preventive maintenance
13	2	3	5	L	
14	2	3	5	L	
15	3	3	6	M	Ensure proper cleaning, shorter intervals btw. preventive maintenance
16	3	2	5	L	
17	2	3	5	L	
18	3	3	6	M	Shorter interval between preventive maintenance
19	3	3	6	M	Ensure proper cleaning, shorter interval btw. preventive maintenance
20	3	2	5	L	
21	2	3	5	L	
22	3	3	6	M	Shorter interval between preventive maintenance
23	4	3	7	M	Ensure proper cleaning, shorter intervals btw. preventive maintenance
24	4	2	6	M	Ensure proper sealing, shorter intervals btw. Preventive maintenance
25	4	3	7	M	Shorter intervals between preventive maintenance
26	4	3	7	M	Shorter intervals between preventive maintenance
27	2	3	5	L	
28	3	2	5	L	
29	2	3	5	L	
30	2	3	5	L	

FMECA ID	Consequence	Probability	Criticality		Action Items
31	3	4	7	M	Ensure proper freq. analysis, shorter intervals between preventive maintenance
32	3	2	5	L	
33	3	3	6	M	Ensure proper freq. analysis, shorter intervals between preventive maintenance
34	3	3	6	M	Ensure proper freq. analysis, shorter intervals between preventive maintenance
35	2	3	5	L	
36	3	2	5	L	
37	2	3	5	L	
38	2	3	5	L	
39	2	3	5	L	
40	3	2	5	L	
41	2	3	5	L	
42	2	3	5	L	
43	3	3	6	M	Ensure proper cleaning, shorter intervals btw. preventive maintenance
44	3	2	5	L	
45	3	3	6	M	Shorter interval between preventive maintenance
46	3	3	6	M	Shorter interval between preventive maintenance
47	3	3	6	M	Ensure proper freq. analysis, shorter intervals between preventive maintenance
48	3	2	5	L	
49	3	3	6	M	Shorter interval between preventive maintenance
50	3	3	6	M	Shorter interval between preventive maintenance
51	3	3	6	M	Shorter interval between preventive maintenance
52	3	3	6	M	Ensure proper cleaning, shorter intervals btw. preventive maintenance
53	3	2	5	L	
54	3	3	6	M	Shorter interval between preventive maintenance
55	3	3	6	M	Shorter interval between preventive maintenance
56	3	3	6	M	Shorter interval between preventive maintenance
57	3	3	6	M	Ensure proper cleaning, shorter intervals btw. preventive maintenance
58	3	2	5	L	
59	3	3	6	M	Shorter interval between preventive maintenance
60	3	3	6	M	Shorter interval between preventive maintenance

FMECA ID	Consequence	Probability	Criticality		Action Items
61	3	3	6	M	Shorter interval between preventive maintenance
62	5	2	7	M	Regular inspection to be added to the operational manual
63	5	2	7	M	Regular inspection to be added to the operational manual
64	5	3	8	H	Ensure proper cleaning, shorter intervals btw. preventive maintenance
65	4	2	6	M	Ensure proper nozzle structure, shorter intervals between preventive maintenance
66	5	3	8	H	Ensure proper cleaning, shorter intervals btw. preventive maintenance
67	4	2	6	M	Ensure proper nozzle structure, shorter intervals between preventive maintenance
68	5	3	8	H	Ensure proper cleaning, shorter intervals btw. preventive maintenance
69	4	2	6	M	Ensure proper nozzle structure, shorter intervals between preventive maintenance
70	3	3	6	M	Ensure proper cleaning, shorter intervals btw. preventive maintenance
71	3	3	6	M	Ensure proper cleaning, shorter intervals btw. preventive maintenance
72	3	3	6	M	Ensure proper cleaning, shorter intervals btw. preventive maintenance
73	3	3	6	M	Ensure proper cleaning, shorter intervals btw. preventive maintenance
74	5	2	7	M	Regular inspection to be added to the operational manual
75	5	2	7	M	Regular inspection to be added to the operational manual
76	4	3	7	M	Ensure proper cleaning, shorter intervals btw. preventive maintenance
77	4	2	6	M	Ensure proper nozzle structure, shorter intervals between preventive maintenance
78	4	3	7	M	Ensure proper cleaning, shorter intervals btw. preventive maintenance
79	4	2	6	M	Ensure proper nozzle structure, shorter intervals between preventive maintenance
80	5	3	8	H	Ensure proper cleaning, shorter intervals btw. preventive maintenance, add a sensor
81	4	2	6	M	Visual inspection of the tank to be added in the operating manual
82	4	2	6	M	Visual inspection of the tank to be added in the operating manual
83	2	2	4	L	
84	3	2	5	L	
85	2	3	5	L	
86	3	2	5	L	
87	2	3	5	L	
88	2	3	5	L	
89	3	4	7	M	Ensure proper freq. analysis, shorter intervals between preventive maintenance
90	3	2	5	L	

FMECA ID	Consequence	Probability	Criticality		Action Items
91	3	3	6	M	Ensure proper freq. analysis, shorter intervals between preventive maintenance
92	3	3	6	M	Ensure proper freq. analysis, shorter intervals between preventive maintenance
93	2	3	5	L	
94	3	2	5	L	
95	2	3	5	L	
96	2	3	5	L	
97	2	3	5	L	
98	3	2	5	L	
99	2	3	5	L	
100	2	3	5	L	
101	2	3	5	L	
102	3	2	5	L	
103	2	3	5	L	
104	2	3	5	L	
105	3	4	7	M	Ensure proper freq. analysis, shorter intervals between preventive maintenance
106	3	2	5	L	
107	3	3	6	M	Ensure proper freq. analysis, shorter intervals between preventive maintenance
108	3	3	6	M	Ensure proper freq. analysis, shorter intervals between preventive maintenance
109	2	3	5	L	
110	3	2	5	L	
111	2	3	5	L	
112	2	3	5	L	
113	4	3	7	M	Ensure proper cleaning, shorter intervals btw. preventive maintenance
114	4	2	6	M	Regular inspection to be added to the operational manual
115	2	3	5	L	
116	3	2	5	L	
117	2	3	5	L	
118	2	3	5	L	
119	2	3	5	L	
120	3	2	5	L	

FMECA ID	Consequence	Probability	Criticality		Action Items
121	2	3	5	L	
122	2	3	5	L	
123	2	3	5	L	
124	3	2	5	L	
125	3	3	6	M	Shorter intervals between preventive maintenance
126	2	3	5	L	
127	2	3	5	L	
128	3	3	6	M	Ensure proper cleaning, shorter intervals btw. preventive maintenance
129	3	2	5	L	
130	3	3	6	M	Shorter intervals between preventive maintenance
131	3	3	6	M	Shorter intervals between preventive maintenance
132	3	3	6	M	Shorter intervals between preventive maintenance
133	2	3	5	L	
134	3	2	5	L	
135	2	3	5	L	
136	2	3	5	L	
137	3	4	7	M	Ensure proper freq. analysis, shorter intervals between preventive maintenance
138	3	2	5	L	
139	3	3	6	M	Ensure proper freq. analysis, shorter intervals between preventive maintenance
140	3	3	6	M	Ensure proper freq. analysis, shorter intervals between preventive maintenance
141	2	3	5	L	
142	3	2	5	L	
143	2	3	5	L	
144	2	3	5	L	
145	2	3	5	L	
146	3	2	5	L	
147	2	3	5	L	
148	2	3	5	L	
149	3	3	6	M	Ensure proper cleaning, shorter intervals btw. preventive maintenance
150	3	2	5	L	
151	3	3	6	M	Shorter intervals between preventive maintenance
152	3	3	6	M	Shorter intervals between preventive maintenance
153	3	3	6	M	Shorter intervals between preventive maintenance

I. Low Risk in FMECA, Exhaust Gas Cleaning System, Wärtsilä

Table I.1: Compoents with low risk in FMECA, exhaust gas scrubber system

System	Abnormal output	External leakage	Fail to close on demand	Fail to control	Fail to open on demand	Plugged/choked	Spurious operation	Structural deficiency	Total
Monitoring system	2	4	4				2		12
Inlet monitor	1						1		2
1.01	1						1		2
Manual gate valve		4	4						8
1.02		1	1						2
1.03		1	1						2
1.05 1.06		1	1						2
1.07 1.08		1	1						2
Outlet monitor	1						1		2
1.04	1								1
2.04							1		1
Scrubber system		3							3
Control valve		3							3
3.01		1							1
3.02		1							1
3.03		1							1
Scrubbing water supply pump inlet		5	3		3	3			14
Check valve		1	1		1	1			4
2.05 2.09 2.13 2.17 2.21		1	1		1	1			4
Manual gate valve		3	2		2	2			9
2.22		1							1
2.02 2.06 2.10 2.14 2.18		1	1		1	1			4
2.04 2.08 2.12 2.16 2.20		1	1		1	1			4
Pump		1							1
2.03 2.07 2.11 2.15 2.19		1							1
Scrubbing water supply pump outlet		3	2		2	2			9
Manual gate valve		2	2		2	2			8
5.01 5.04 5.07		1	1		1	1			4
5.03 5.06 5.09		1	1		1	1			4
Pump		1							1
5.02 5.05 5.08		1							1
Water outlet		2	1		1	1			5
Check valve		1	1		1	1			4
6.01		1	1		1	1			4

Control valve		1							1
6.02		1							1
Water treatment system		12	7	1	8	8		1	37
Check valve		2	2		2	2			8
4.06		1	1		1	1			4
4.12 4.19 4.26 4.33		1	1		1	1			4
Control valve		2		1	1	1			5
4.35		1							1
4.13 4.20 4.27 4.34		1		1	1	1			4
Manual gate valve		5	5		5	5			20
4.03		1	1		1	1			4
4.05		1	1		1	1			4
4.07 4.14 4.21 4.28		1	1		1	1			4
4.09 4.16 4.23 4.30		1	1		1	1			4
4.11 4.18 4.25 4.32		1	1		1	1			4
Pump		2							2
4.04		1							1
4.08 4.15 4.22 4.29		1							1
Sludge tank		1						1	2
4.02		1						1	2
Total	**2**	**29**	**17**	**1**	**14**	**14**	**2**	**1**	**80**

J. Medium Risk in FMECA, Exhaust Gas Cleaning System, Wärtsilä

Table J.1: Components with medium risk in FMECA, exhaust gas scrubber system

System	External leakage	Fail to close on demand	Fail to control	Fail to function on demand	Fail to open on demand	Fail to start on demand	Fall down	Plugged /choked	Spurious stop	Structural deficiency	Vibration	Total
Monitoring system				2	4			4				10
Inlet monitor				1								1
1.01				1								1
Manual gate valve					4			4				8
1.02					1			1				2
1.03					1			1				2
1.05 1.06					1			1				2
1.07 1.08					1			1				2
Outlet monitor				1								1
1.04				1								1
Scrubber system	2	3	3		3		5	9		2		27
Control valve		3	3		3			3				12
3.01		1	1		1			1				4
3.02		1	1		1			1				4
3.03		1	1		1			1				4
Droplet separator								1				1
3.09								1				1
Injection nozzle							5	2				7
3.05							1					1
3.06							1					1
3.07							1					1
3.13							1	1				2
3.14							1	1				2
Packed bed								2				2
3.1								1				1
3.11								1				1
Scrubber device	1									1		2
3.04	1									1		2
Steam cleaning								1				1
3.08								1				1
Venturi	1									1		2
3.12	1									1		2
Scrubbing water supply pump inlet	1	2			2	1		2	1		1	10
Manual gate valve	1	2			2			2				7
2.01	1	1			1			1				4
2.22		1			1			1				3
Pump						1			1		1	3
2.03 2.07 2.11 2.15 2.19						1			1		1	3
Scrubbing water supply pump outlet						1			1		1	3

Pump						1			1		1	3
5.02 5.05 5.08						1			1		1	3
Water outlet		1	1		1			1				4
Control valve		1	1		1			1				4
6.02		1	1		1			1				4
Water treatment system	1	2	1		1	2		2	2	2	2	15
Control valve		2	1		1			1				5
4.35		1	1		1			1				4
4.13 4.20 4.27 4.34		1										1
Hydrocyclone								1		1		2
4.10 4.17 4.24 4.31								1		1		2
Pump						2			2		2	6
4.04						1			1		1	3
4.08 4.15 4.22 4.29						1			1		1	3
Residence tank	1									1		2
4.01	1									1		2
Total	**4**	**8**	**5**	**2**	**11**	**4**	**5**	**18**	**4**	**4**	**4**	**69**

K. High Risk in FMECA, Exhaust Gas Cleaning System, Wärtsilä

Table K.1: Components with high risk in FMECA, exhaust gas scrubber system

System	Plugged/choked	Total
Scrubber system	4	4
Drainpipe	1	1
3.15	1	1
Injection nozzle	3	3
3.05	1	1
3.06	1	1
3.07	1	1
Total	**4**	**4**

L. Hand Calculation of Fault Trees

This appendix describes the mathematical background on how to calculate the availability of a fault tree, on the basis of basic events with repairable failure data. Further, the availability's of the six fault trees in Section 5.2.2 are calculated by utilising the presented hand calculation method.

Background

It is given in software CARA-FaultTree that a repairable unit has the two following reliability parameters: repair time, τ, and failure rate, λ. Repair time is specified in hours, while failure rate is the expected number of failures per hours/per 10^6 hours (Sydvest Software 2000).

Repairable units are components that are repaired when a failure occurs. If the failure rate, λ, and the mean time to repair (MTTR), τ, are given, CARA-FaultTree computes unavailability of item i at time t, $q_i(t)$, by the following formula (Sydvest Software 2000, Rausand 2011):

$$q_i(t) = \frac{\lambda\tau}{1+\lambda\tau}(1 - e^{\frac{(1+\lambda\tau)t}{\tau}}) \tag{L.1}$$

By letting t tend to infinity, the following approximation can be obtained (Sydvest Software 2000):

$$q_i = \frac{\text{MTTR}}{\text{MTTR+MTTF}} \tag{L.2}$$

where

$$\text{MTTF} = \frac{1}{\lambda}$$

which is minimal if the set cannot be reduced without losing its status as a cut set.

Cut sets provide information about the possible combinations of basic events. CARA-FaultTree identifies minimal cut sets by utilising the algorithm MOCUS (ref. Section 3.1.2).

Let C_k denote the k minimal cut sets of a fault tree, and let $C_j(t)$ be the event when cut set C_j is failed at time t, for j = 1,2,...,k. The top event occurs at time t when one or more minimal cut sets fails at time t. Hence, top event can be expressed (Rausand 2011):

$$top(t) = C_1(t) \cup C_2(t) \cup \ldots \cup C_k(t) \tag{L.3}$$

From (3), the top event probability at time t, $Q_0(t)$, can be written:

$$Q_0\,(t) = Pr(TOP(t)) = Pr(C_1(t) \cup C_2(t) \cup \ldots \cup C_k(t) \quad \text{(L.4)}$$

where $C_j(t)$ is the probability that minimal cut set j is failed at time t.

Further, minimal cut set j fails at time t when all the basic events $E_{j,i}$ in C_j occur at time t. Therefore, the failure of minimal cut set, $C_i(t)$, is represented as a fault tree with a single AND-gate. Let $\check{Q}_j(t)$ denote the probability that minimal cut set C_j fails at time t, and n_j is the number of basic events in minimal cut set C_j. From (4), if all the basic events in minimal cut set C_j are independent, the probability is written:

$$\check{Q}_j(t) = Pr(E_{j,1}(t) \cap E_{j,2}(t) \cap \ldots \cap E_{j,n_j}) \quad \text{(L.5)}$$

$$= \prod_{i \epsilon C_j} q_i(t)$$

If all the minimal cut sets were independent, formula 6 could be employed to determine the probability of the top event at time t, $Q_0(t)$. This formula is extracted from top event probability of a fault tree with a singe or-gate.

$$Q_0\,(t) = 1 - \prod_{j=1}^{k}(1 - \check{Q}_j\,(t)) \quad \text{(L.6)}$$

Minimal cut sets are generally not independent, since a basic event will often be a member of several minimal cut sets. Hence, there is a positive association between the minimal cut sets, and formula 6 can be rewritten to the following approximation:

$$Q_0\,(t) \lessapprox 1 - \prod_{j=1}^{k}(1 - \check{Q}_j\,(t)) \quad \text{(L.7)}$$

Formula 7 is the upper bound formula, which is one of the methods used in CARA-FaultTree. The formula will give a satisfying approximation. However, since it is conservative, the top event probability, $Q_0(t)$, is less than the value calculated (Rausand 2011).

Additionally, for hand calculations, the following formula may be used to determine the probability of the top event at time t, $Q_0(t)$. It is obtained from formula 7 and neglects simultaneous failures of two or more minimal cut sets. The neglecting is feasible since the probability of simultaneous failures is very small so that the approximation is accurate enough.

$$Q_0\,(t) \lesssim \sum_{j=1}^{k} \check{Q}_j(t) \tag{L.8}$$

Formula 9 shows why formula 8 is seen to be more conservative compared to the upper bound approximation.

$$Q_0\,(t) \lesssim 1 - \prod_{j=1}^{k} [1 - \check{Q}_j\,(t)] \leq \sum_{j=1}^{k} \check{Q}_j(t) \tag{L.9}$$

Hand Calculation of top event probabilities

Hand calculations of the top event probabilities of the six fault trees, constructed in Section 5.2.2, are calculated with formula 2, formula 7, and formula 8.

Unavailability of item i at time t, $q_i(t)$, is computed for each fault tree with formula 2. Further, the probability that minimal cut set C_j fails at time t, $\check{Q}_j(t)$, is calculated based on minimal cut sets with one and two components, with formula 5. Fault tree one (overpressure in scrubber device and venturi), fault tree two (no seawater to scrubber device and venturi), and fault tree six (exhaust gas not washed in scrubber device) have cut sets with three components. They have 270, 2179 and 2179 numbers of cut sets with three components, respectively. However, these are not included because of the probability of simultaneous failures is very small so that the approximation is assumed to be accurate enough with one and two components.

Table L.1 to Table L.6 show the calculated values of probability that minimal cut set C_j fails at time t, $\check{Q}_j(t)$, for minimal cut sets C_j, in each fault tree. Note in Table L.4, fault tree four, Outlet monitor 1.4 does not measure pH, PAH, turbidity and temperature, has only cut sets with two components.

Table L.7 displays the calculated probabilities of top event at time t, $Q_0(t)$, for each fault tree. The probabilities are calculated by using formula 7 and formula 8. Formula 8 neglects simultaneous failures of two or more minimal cut sets.

Table L.1: Cut sets with one and two components in fault tree one

Cut set(s) with 1 Component		Cut set(s) with 2 Component	
Minimal cut set C_j	Probability $\check{Q}_j(t)$	Minimal cut set C_j	Probability $\check{Q}_j(t)$
{Basic 6}	0.85311	{Basic 23,Basic 25}	0.67464
{Basic 7}	0.76382	{Basic 23,Basic 26}	0.33362
{Basic 4}	0.82136	{Basic 24,Basic 25}	0.33362
{Basic 5}	0.82136	{Basic 24,Basic 26}	0.16498
{Basic 33}	0.96043	{Basic 23,Basic 27}	0.67464
{Basic 34}	0.96043	{Basic 23,Basic 28}	0.33362
{Basic 35}	0.96043	{Basic 24,Basic 27}	0.33362
{Basic 36}	0.96043	{Basic 24,Basic 28}	0.16498
{Basic 37}	0.96043	{Basic 25,Basic 27}	0.67464
{Basic 38}	0.96684	{Basic 25,Basic 28}	0.33362
{Basic 1}	0.82136	{Basic 26,Basic 27}	0.33362
{Basic 2}	0.82136	{Basic 26,Basic 28}	0.16498
{Basic 3}	0.95825		

Table L.2: Cut sets with one and two components in fault tree two

Cut set(s) with 1 Component		Cut set(s) with 2 Component	
Minimal cut set C_j	Probability $\check{Q}_j(t)$	Minimal cut set C_j	Probability $\check{Q}_j(t)$
{Basic 1}	0.86856	{Basic 3,Basic 4}	0.83997
{Basic 2}	0.86856	{Basic 3,Basic 5}	0.83997

Table L.3: Cut sets with one and two components in fault tree three

Cut set(s) with 1 Component		Cut set(s) with 2 Component	
Minimal cut set C_j	Probability $\check{Q}_j(t)$	Minimal cut set C_j	Probability $\check{Q}_j(t)$
{Basic 1}	0.28058	{Basic 7,Basic 8}	0.45815
{Basic 2}	0.85207	{Basic 7,Basic 9}	0.41020
{Basic 3}	0.86856	{Basic 8,Basic 9}	0.65162
{Basic 4}	0.58194		
{Basic 5}	0.19355		
{Basic 6}	0.39394		

Table L.4: Cut sets with two components in fault tree four

Cut set(s) with 2 Component		Cut set(s) with 2 Component	
Minimal cut set C_j	Probability $\check{Q}_j(t)$	Minimal cut set C_j	Probability $\check{Q}_j(t)$
{Basic 4,Basic 10}	0.07872	{Basic 7,Basic 12}	0.50545
{Basic 4,Basic 11}	0.23907	{Basic 7,Basic 13}	0.33865
{Basic 4,Basic 12}	0.24370	{Basic 7,Basic 14}	0.11263
{Basic 4,Basic 13}	0.16328	{Basic 7,Basic 15}	0.22925
{Basic 4,Basic 14}	0.05430	{Basic 8,Basic 10}	0.07872
{Basic 4,Basic 15}	0.11053	{Basic 8,Basic 11}	0.23907
{Basic 5,Basic 10}	0.23907	{Basic 8,Basic 12}	0.24370
{Basic 5,Basic 11}	0.72602	{Basic 8,Basic 13}	0.16328
{Basic 5,Basic 12}	0.74007	{Basic 8,Basic 14}	0.05430
{Basic 5,Basic 13}	0.49585	{Basic 8,Basic 15}	0.11053

{Basic 5,Basic 14}	0.16492	{Basic 9,Basic 10}	0.23907
{Basic 5,Basic 15}	0.33566	{Basic 9,Basic 11}	0.72602
{Basic 6,Basic 10}	0.24370	{Basic 9,Basic 12}	0.74007
{Basic 6,Basic 11}	0.74007	{Basic 9,Basic 13}	0.49585
{Basic 6,Basic 12}	0.75440	{Basic 9,Basic 14}	0.16492
{Basic 6,Basic 13}	0.50545	{Basic 9,Basic 15}	0.33566
{Basic 6,Basic 14}	0.16811	{Basic 1,Basic 2}	0.45815
{Basic 6,Basic 15}	0.34216	{Basic 1,Basic 3}	0.41020
{Basic 7,Basic 10}	0.16328	{Basic 2,Basic 3}	0.65162
{Basic 7,Basic 11}	0.49585		

Table L.5: Cut sets with one and two components in fault tree five

Cut set(s) with 1 Component		Cut set(s) with 2 Component	
Minimal cut set C_j	Probability $\check{Q}_j(t)$	Minimal cut set C_j	Probability $\check{Q}_j(t)$
{Basic 1}	0.53704	{Basic 9,Basic 21}	0.16498
{Basic 2}	0.85311	{Basic 14,Basic 18}	0.86605
{Basic 3}	0.76382	{Basic 14,Basic 19}	0.92559
{Basic 5}	0.40618	{Basic 14,Basic 20}	0.89653
{Basic 6}	0.53704	{Basic 14,Basic 17}	0.37799
{Basic 7}	0.85311	{Basic 15,Basic 18}	0.92559
{Basic 4}	0.76382	{Basic 15,Basic 19}	0.98922
{Basic 8}	0.40618	{Basic 15,Basic 20}	0.95817
Cut set(s) with 2 Component		{Basic 15,Basic 17}	0.40398
Minimal cut set C_j	Probability $\check{Q}_j(t)$	{Basic 16,Basic 18}	0.89653
{Basic 10,Basic 14}	0.86605	{Basic 16,Basic 19}	0.95817
{Basic 10,Basic 15}	0.92559	{Basic 16,Basic 20}	0.92808
{Basic 10,Basic 16}	0.89653	{Basic 16,Basic 17}	0.39130
{Basic 10,Basic 13}	0.37799	{Basic 13,Basic 18}	0.37799
{Basic 11,Basic 14}	0.92559	{Basic 13,Basic 19}	0.40398
{Basic 11,Basic 15}	0.98922	{Basic 13,Basic 20}	0.39130
{Basic 11,Basic 16}	0.95817	{Basic 13,Basic 17}	0.16498
{Basic 11,Basic 13}	0.40398	{Basic 14,Basic 22}	0.86605
{Basic 12,Basic 14}	0.89653	{Basic 14,Basic 23}	0.92559
{Basic 12,Basic 15}	0.95817	{Basic 14,Basic 24}	0.89653
{Basic 12,Basic 16}	0.92808	{Basic 14,Basic 21}	0.37799
{Basic 12,Basic 13}	0.39130	{Basic 15,Basic 22}	0.92559
{Basic 9,Basic 14}	0.37799	{Basic 15,Basic 23}	0.98922
{Basic 9,Basic 15}	0.40398	{Basic 15,Basic 24}	0.95817
{Basic 9,Basic 16}	0.39130	{Basic 15,Basic 21}	0.40398
{Basic 9,Basic 13}	0.16498	{Basic 16,Basic 22}	0.89653
{Basic 10,Basic 18}	0.86605	{Basic 16,Basic 23}	0.95817
{Basic 10,Basic 19}	0.92559	{Basic 16,Basic 24}	0.92808
{Basic 10,Basic 20}	0.89653	{Basic 16,Basic 21}	0.39130
{Basic 10,Basic 17}	0.37799	{Basic 13,Basic 22}	0.37799
{Basic 11,Basic 18}	0.92559	{Basic 13,Basic 23}	0.40398
{Basic 11,Basic 19}	0.98922	{Basic 13,Basic 24}	0.39130

{Basic 11,Basic 20}	0.95817	{Basic 13,Basic 21}	0.16498
{Basic 11,Basic 17}	0.40398	{Basic 18,Basic 22}	0.86605
{Basic 12,Basic 18}	0.89653	{Basic 18,Basic 23}	0.92559
{Basic 12,Basic 19}	0.95817	{Basic 18,Basic 24}	0.89653
{Basic 12,Basic 20}	0.92808	{Basic 18,Basic 21}	0.37799
{Basic 12,Basic 17}	0.39130	{Basic 19,Basic 22}	0.92559
{Basic 9,Basic 18}	0.37799	{Basic 19,Basic 23}	0.98922
{Basic 9,Basic 19}	0.40398	{Basic 19,Basic 24}	0.95817
{Basic 9,Basic 20}	0.39130	{Basic 19,Basic 21}	0.40398
{Basic 9,Basic 17}	0.16498	{Basic 20,Basic 22}	0.89653
{Basic 10,Basic 22}	0.86605	{Basic 20,Basic 23}	0.95817
{Basic 10,Basic 23}	0.92559	{Basic 20,Basic 24}	0.92808
{Basic 10,Basic 24}	0.89653	{Basic 20,Basic 21}	0.39130
{Basic 10,Basic 21}	0.37799	{Basic 17,Basic 22}	0.37799
{Basic 11,Basic 22}	0.92559	{Basic 17,Basic 23}	0.40398
{Basic 11,Basic 23}	0.98922	{Basic 17,Basic 24}	0.39130
{Basic 11,Basic 24}	0.95817	{Basic 17,Basic 21}	0.16498
{Basic 11,Basic 21}	0.40398	{Basic 9,Basic 23}	0.40398
{Basic 12,Basic 22}	0.89653	{Basic 9,Basic 24}	0.39130
{Basic 12,Basic 23}	0.95817	{Basic 9,Basic 21}	0.16498
{Basic 12,Basic 24}	0.92808	{Basic 14,Basic 18}	0.86605
{Basic 12,Basic 21}	0.39130	{Basic 14,Basic 19}	0.92559
{Basic 9,Basic 22}	0.37799	{Basic 14,Basic 20}	0.89653
{Basic 9,Basic 23}	0.40398	{Basic 14,Basic 17}	0.37799
{Basic 9,Basic 24}	0.39130	{Basic 15,Basic 18}	0.92559

Table L.6: Cut sets with one and two components in fault tree two

Cut set(s) with 1 Component		Cut set(s) with 2 Component	
Minimal cut set C_j	Probability $\check{Q}_j(t)$	Minimal cut set C_j	Probability $\check{Q}_j(t)$
{Basic 1}	0.86856	{Basic 3,Basic 4}	0.83997
{Basic 2}	0.86856	{Basic 3,Basic 5}	0.83997

Table L.7: Hand calculated top event probabilities of fault trees

	Top Event Probability	
Fault Tree	Formula 7	Formula 8
F1	1.00000	11.62964
F2	0.99956	1.73712
F3	0.99968	3.17063
F4	1.00000	-
F5	1.00000	5.12029
F6	0.99956	1.73712

M. F1: Overpressure in Scrubber Device and Venturi

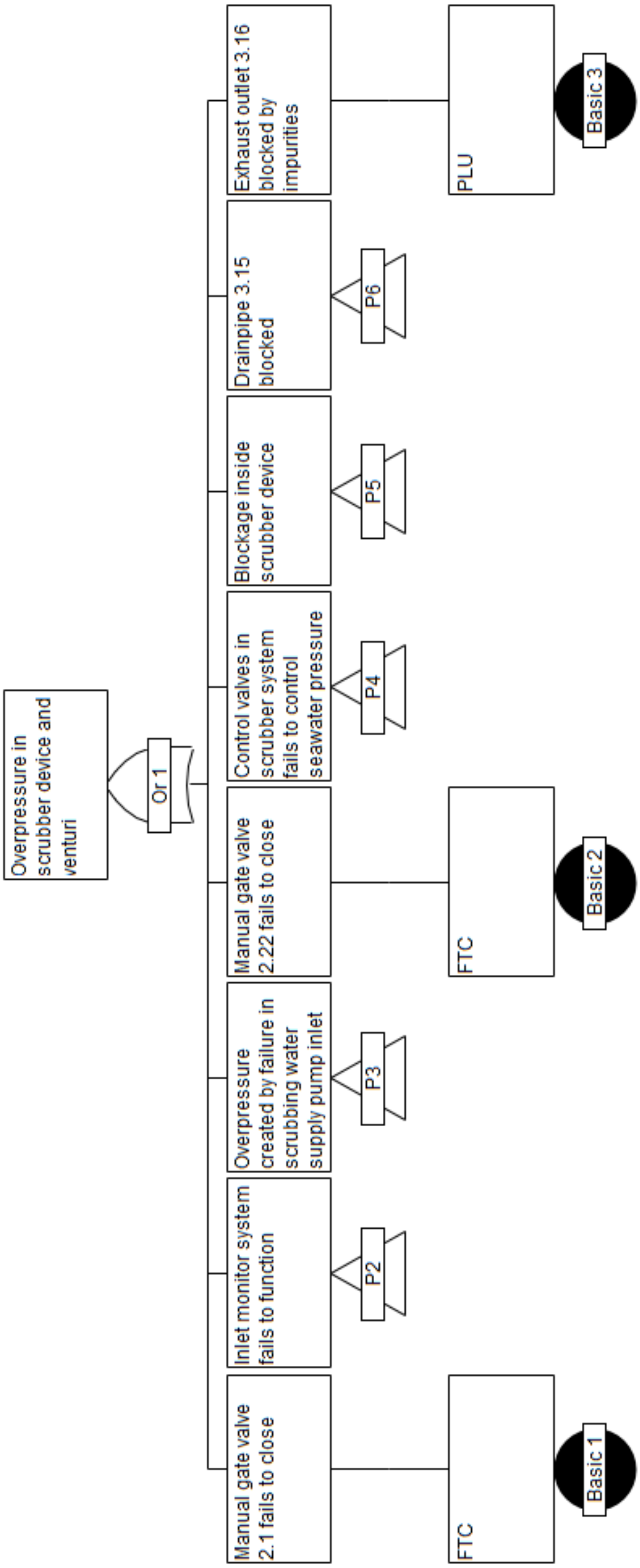
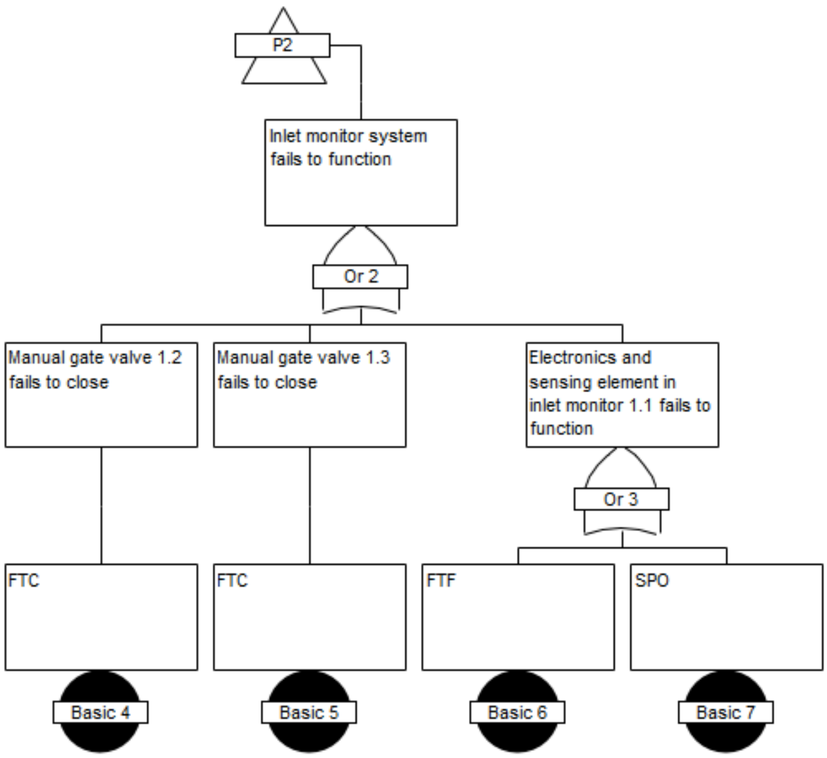
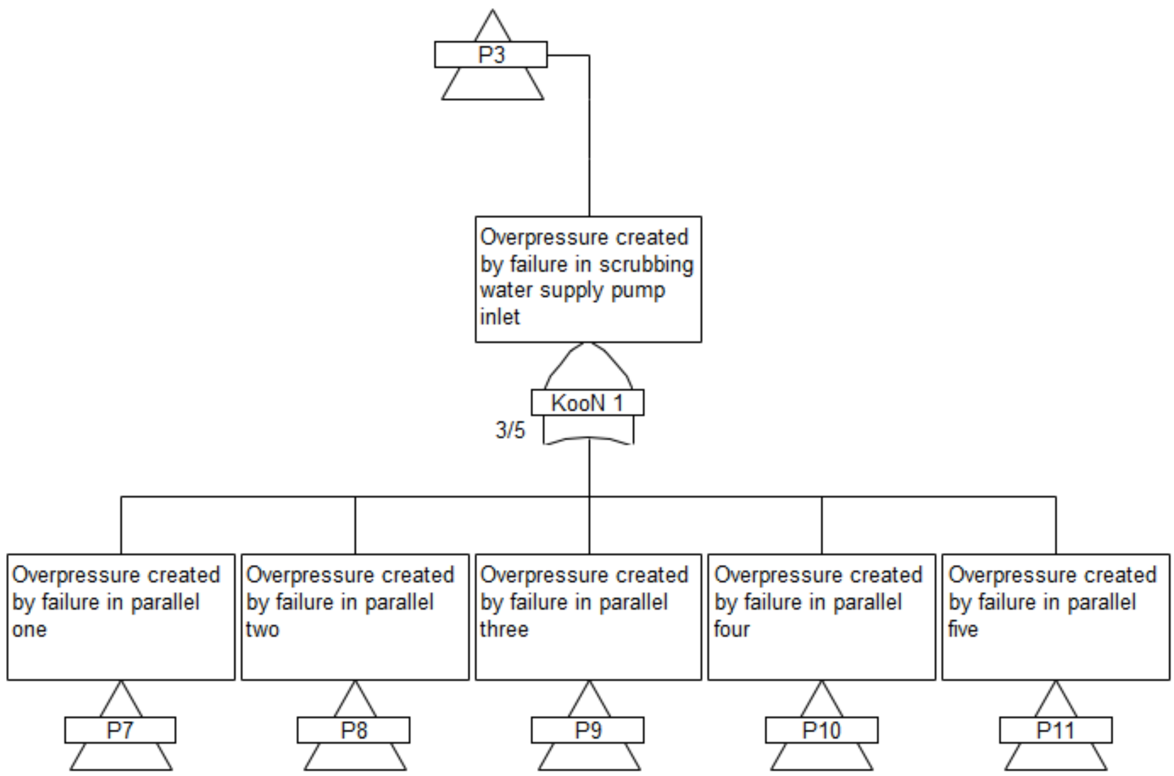


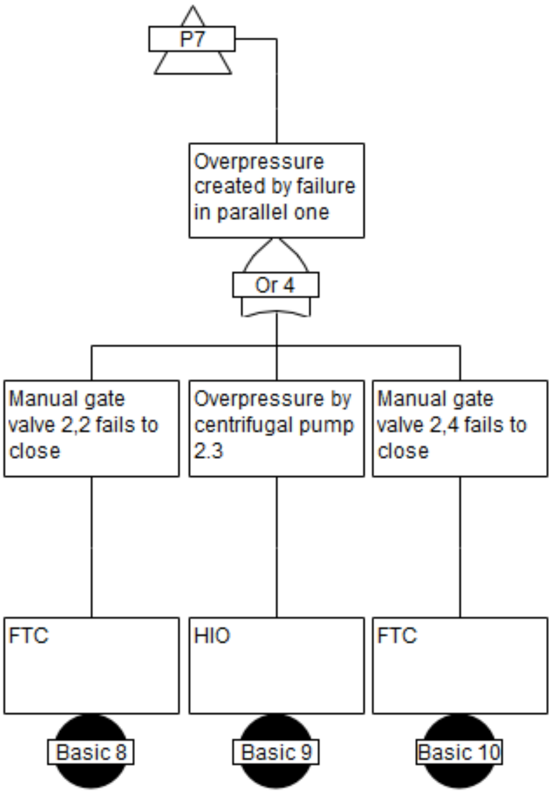
Figure M.1: Fault tree one, Overpressure in scrubber device and venturi

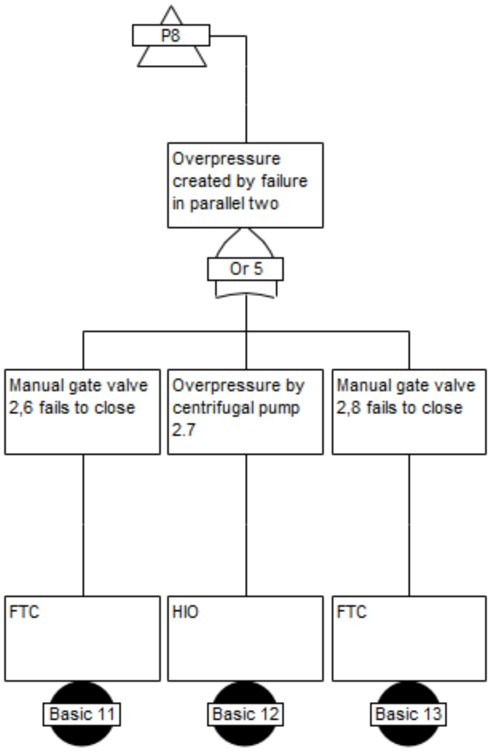


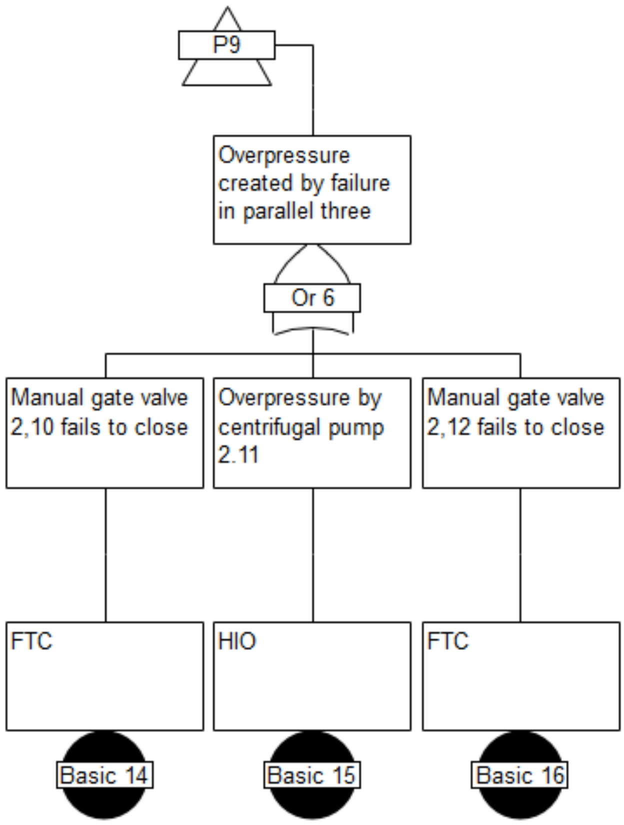
P2
Inlet monitor system fails to function
Or 2
Manual gate valve 1.2 fails to close
Manual gate valve 1.3 fails to close
Electronics and sensing element in inlet monitor 1.1 fails to function
Or 3
FTC
FTC
FTF
SPO
Basic 4
Basic 5
Basic 6
Basic 7

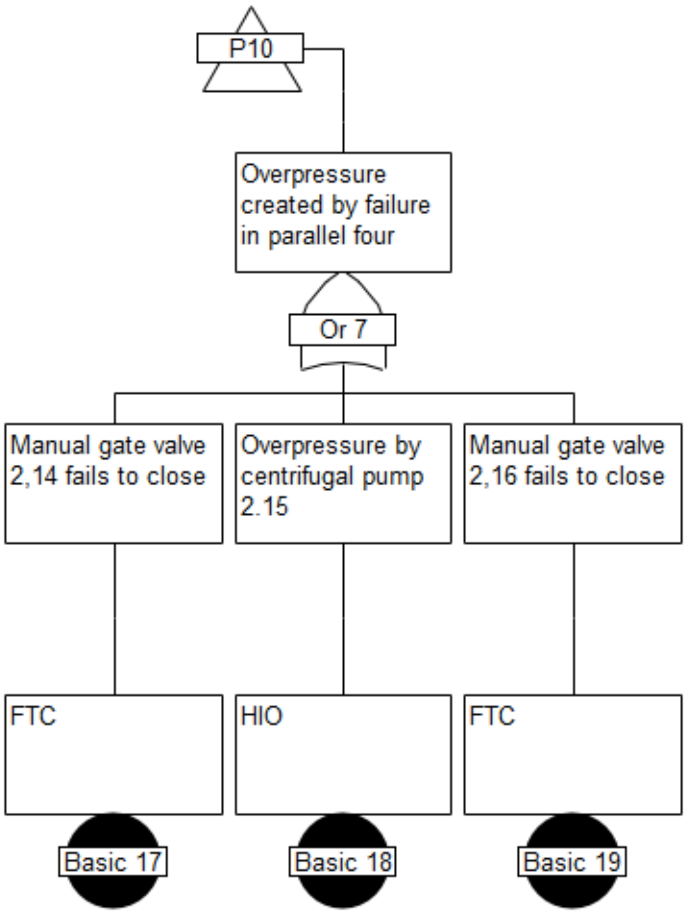


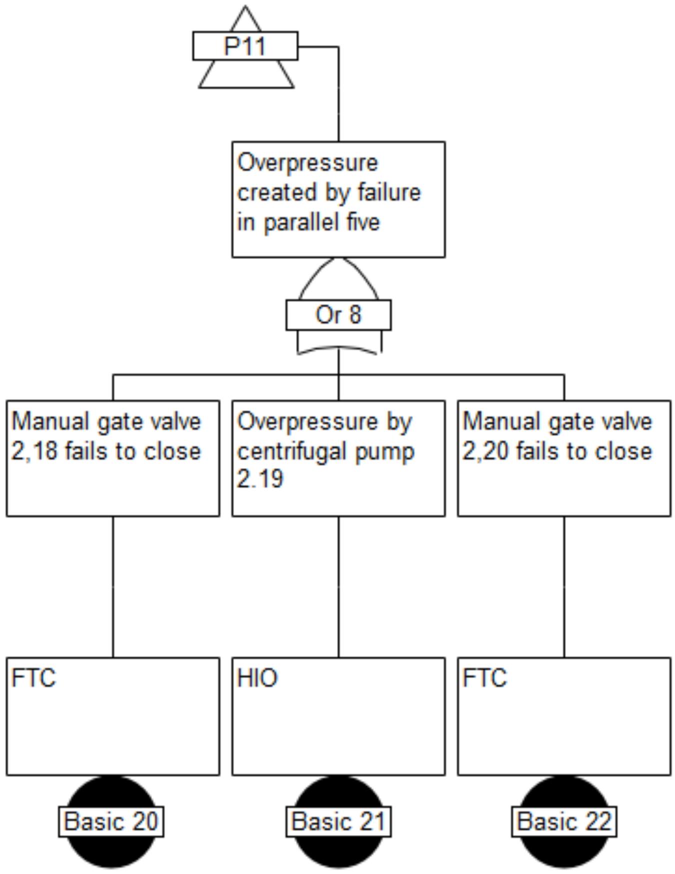
P3
Overpressure created by failure in scrubbing water supply pump inlet
KooN 1
3/5
Overpressure created by failure in parallel one
Overpressure created by failure in parallel two
Overpressure created by failure in parallel three
Overpressure created by failure in parallel four
Overpressure created by failure in parallel five
P7
P8
P9
P10
P11

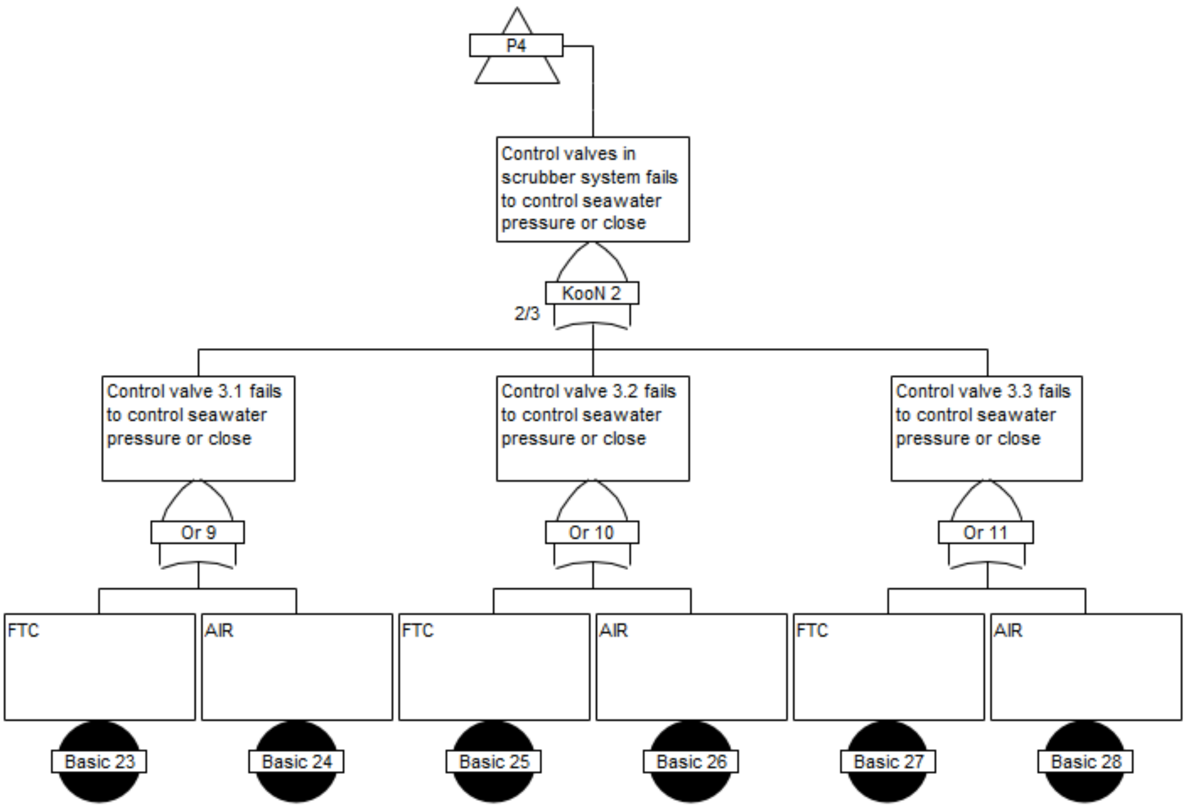

P7
Overpressure created by failure in parallel one
Or 4
Manual gate valve 2,2 fails to close
Overpressure by centrifugal pump 2.3
Manual gate valve 2,4 fails to close
FTC
HIO
FTC
Basic 8
Basic 9
Basic 10

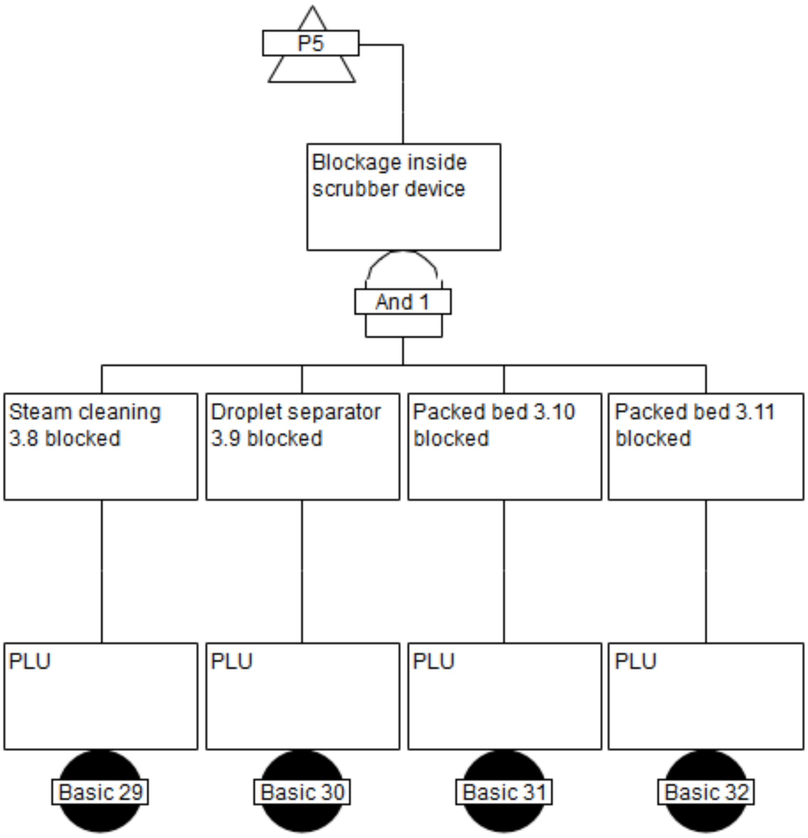

P8
Overpressure created by failure in parallel two
Or 5
Manual gate valve 2,6 fails to close
Overpressure by centrifugal pump 2.7
Manual gate valve 2,8 fails to close
FTC
HIO
FTC
Basic 11
Basic 12
Basic 13

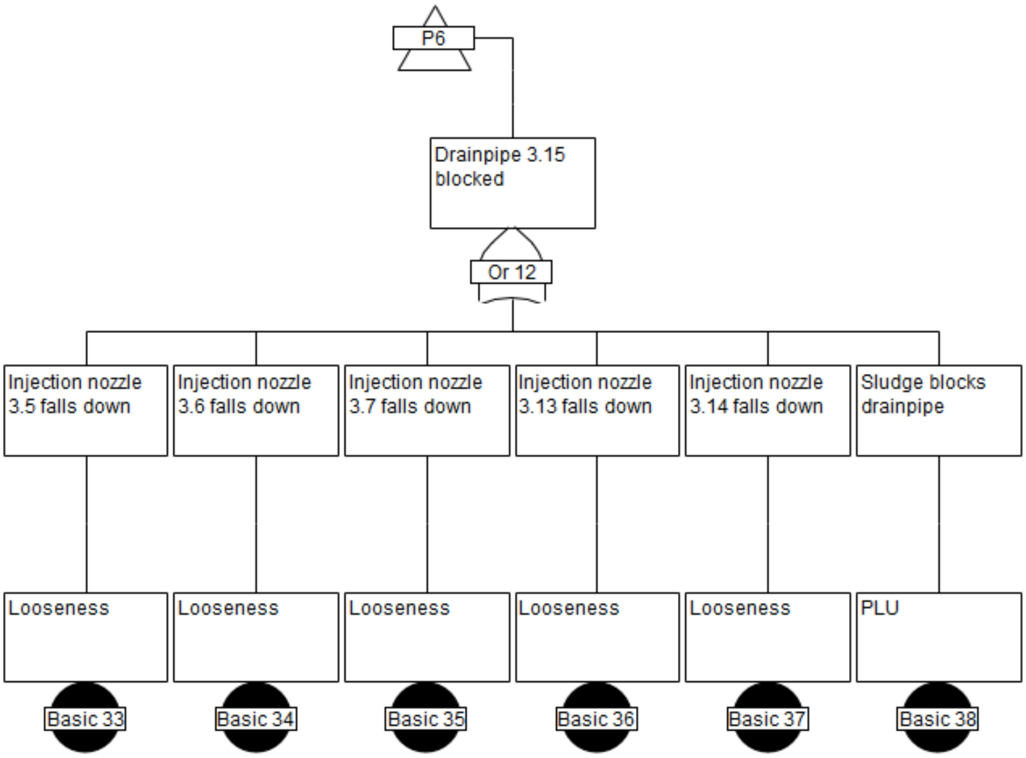

P9
Overpressure created by failure in parallel three
Or 6
Manual gate valve 2,10 fails to close
Overpressure by centrifugal pump 2.11
Manual gate valve 2,12 fails to close
FTC
HIO
FTC
Basic 14
Basic 15
Basic 16


P10
Overpressure created by failure in parallel four
Or 7
Manual gate valve 2,14 fails to close
Overpressure by centrifugal pump 2.15
Manual gate valve 2,16 fails to close
FTC
HIO
FTC
Basic 17
Basic 18
Basic 19


P11
Overpressure created by failure in parallel five
Or 8
Manual gate valve 2,18 fails to close
Overpressure by centrifugal pump 2.19
Manual gate valve 2,20 fails to close
FTC
HIO
FTC
Basic 20
Basic 21
Basic 22


P4
Control valves in scrubber system fails to control seawater pressure or close
KooN 2
2/3
Control valve 3.1 fails to control seawater pressure or close
Control valve 3.2 fails to control seawater pressure or close
Control valve 3.3 fails to control seawater pressure or close
Or 9
Or 10
Or 11
FTC
AIR
FTC
AIR
FTC
AIR
Basic 23
Basic 24
Basic 25
Basic 26
Basic 27
Basic 28


P5
Blockage inside scrubber device
And 1
Steam cleaning 3.8 blocked
Droplet separator 3.9 blocked
Packed bed 3.10 blocked
Packed bed 3.11 blocked
PLU
PLU
PLU
PLU
Basic 29
Basic 30
Basic 31
Basic 32


P6
Drainpipe 3.15 blocked
Or 12
Injection nozzle 3.5 falls down
Injection nozzle 3.6 falls down
Injection nozzle 3.7 falls down
Injection nozzle 3.13 falls down
Injection nozzle 3.14 falls down
Sludge blocks drainpipe
Looseness
Looseness
Looseness
Looseness
Looseness
PLU
Basic 33
Basic 34
Basic 35
Basic 36
Basic 37
Basic 38

N. F2: NO SEAWATER TO SCRUBBER DEVICE AND VENTURI

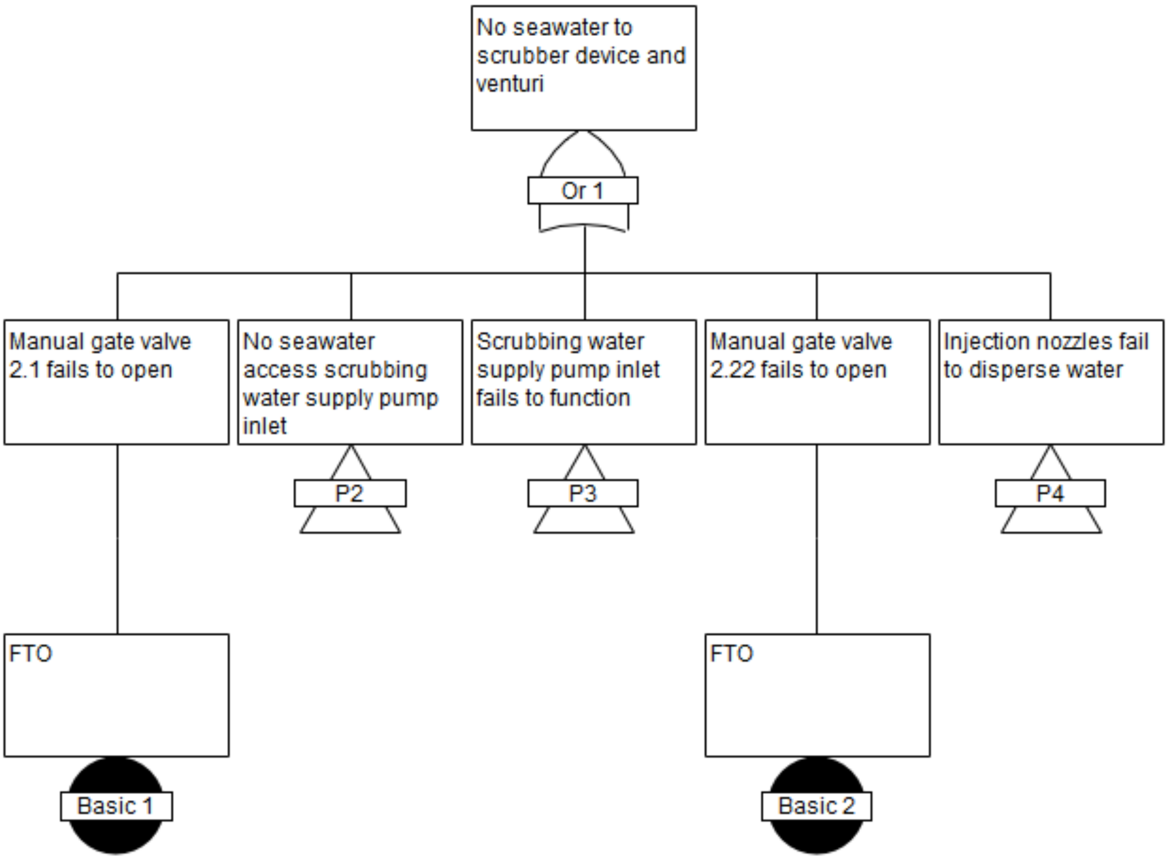
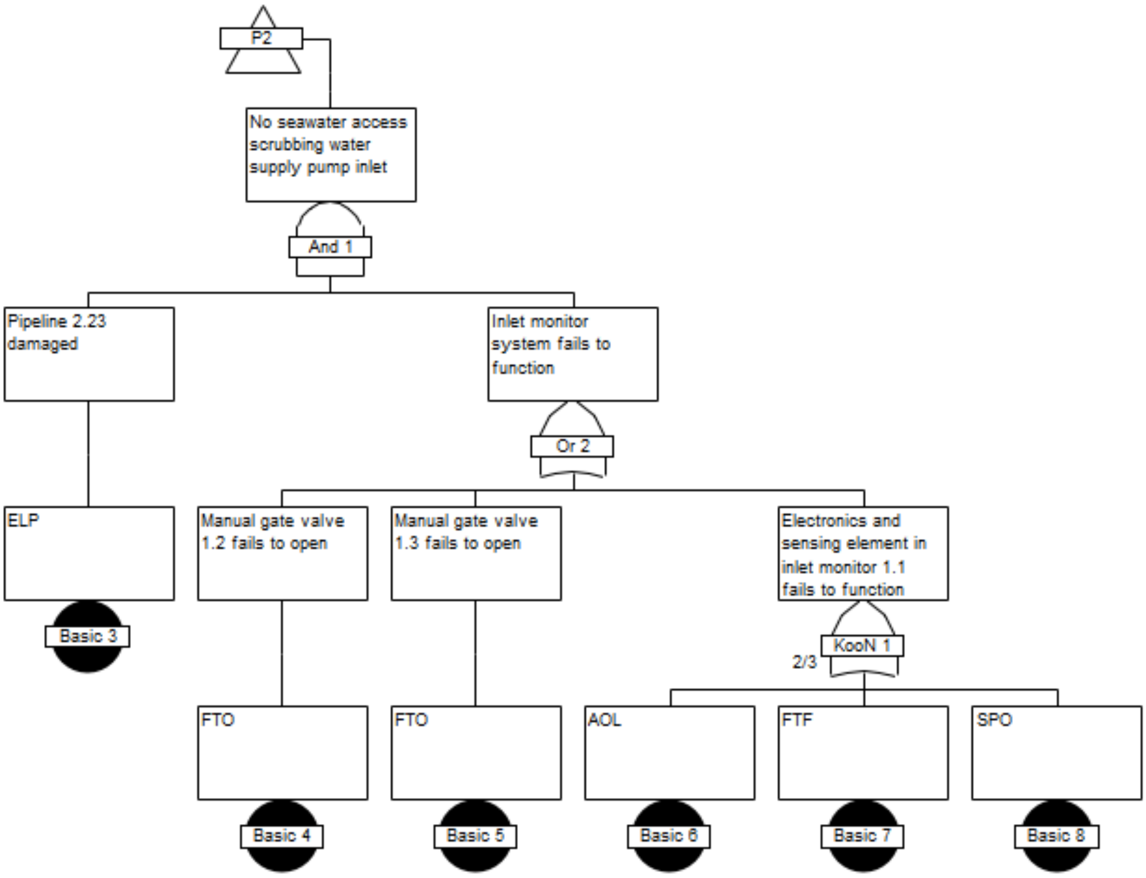
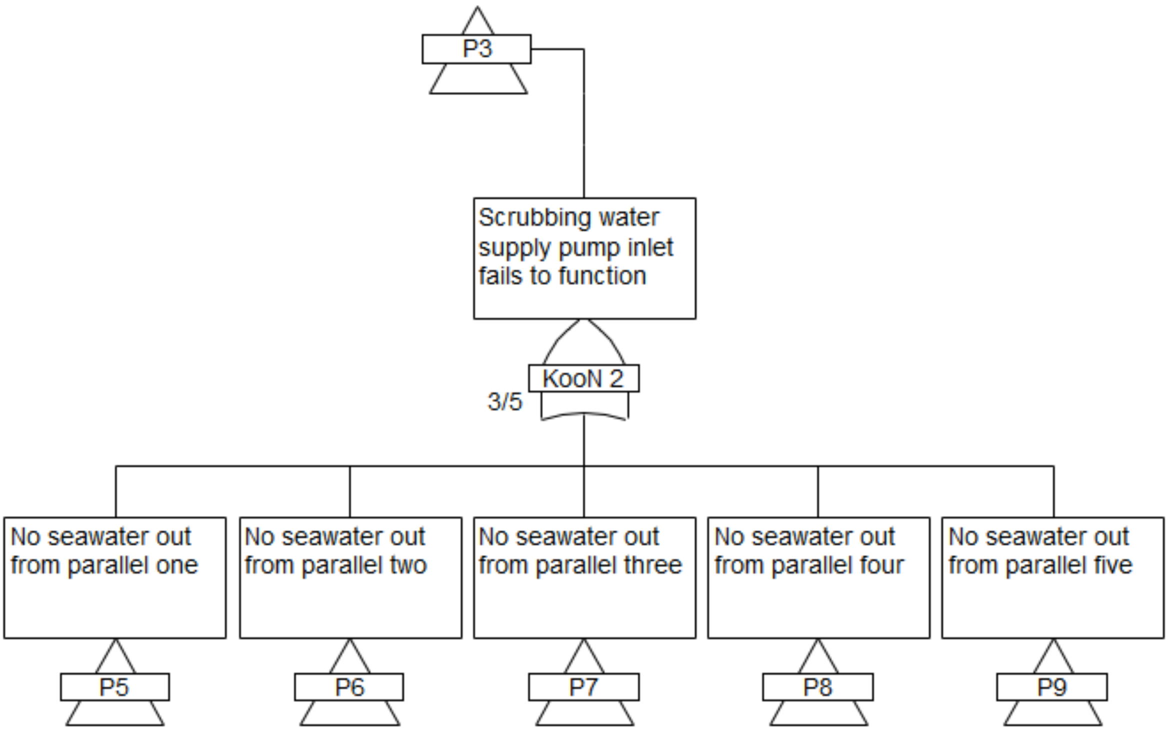
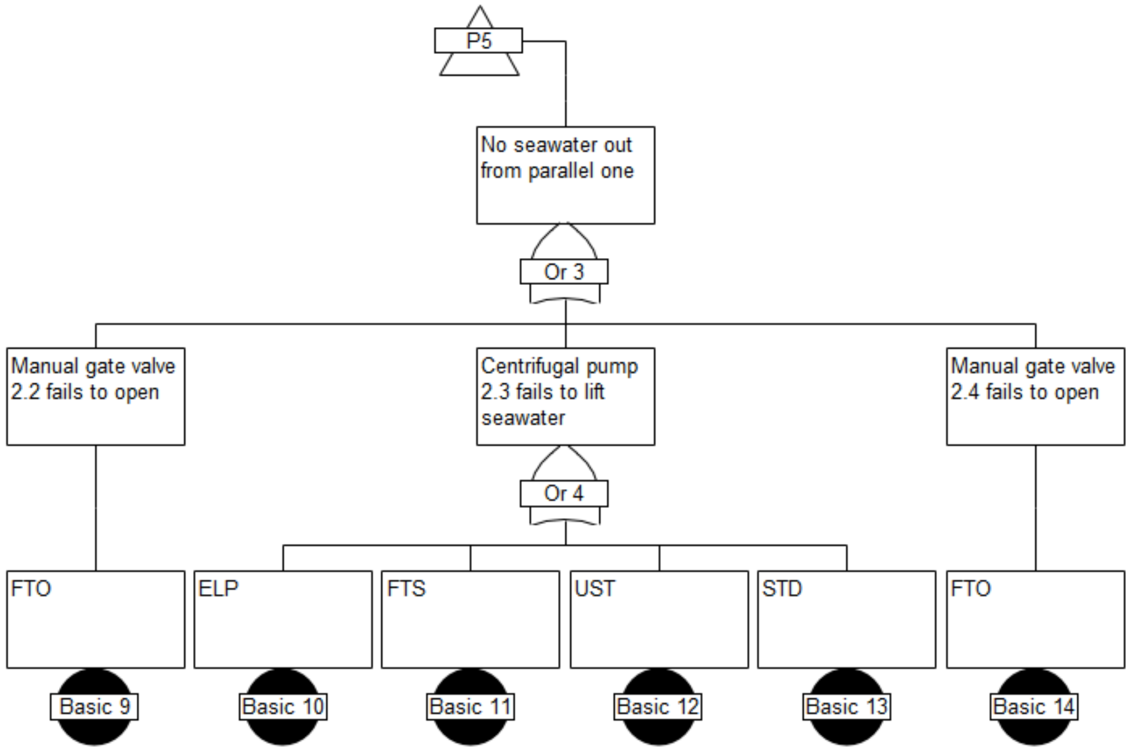
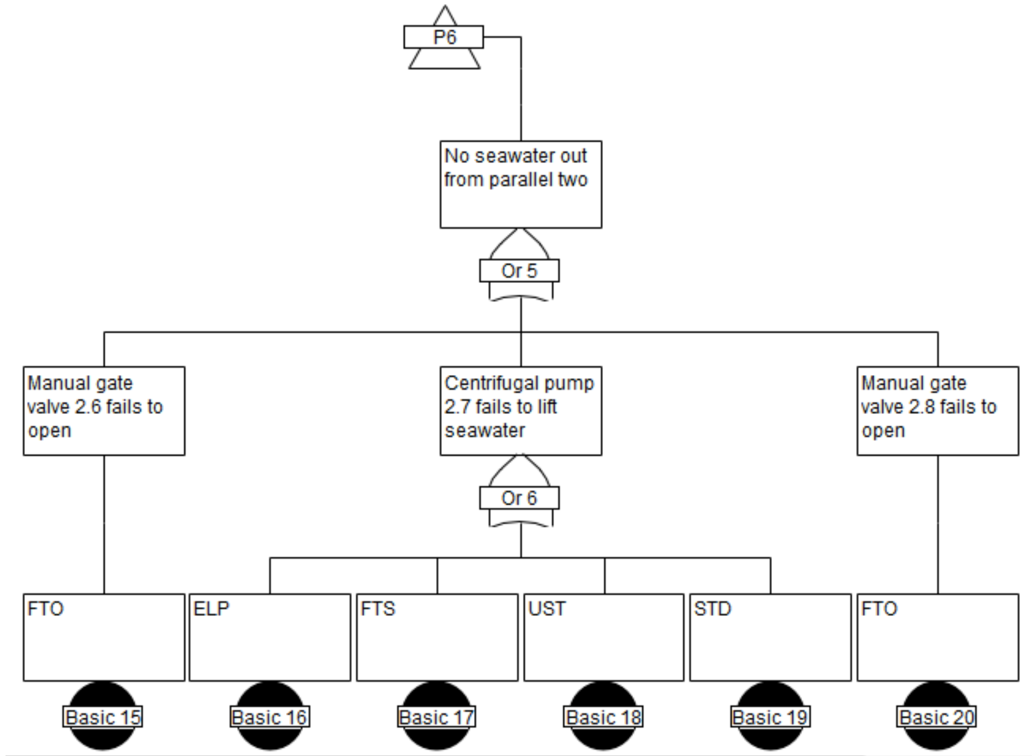


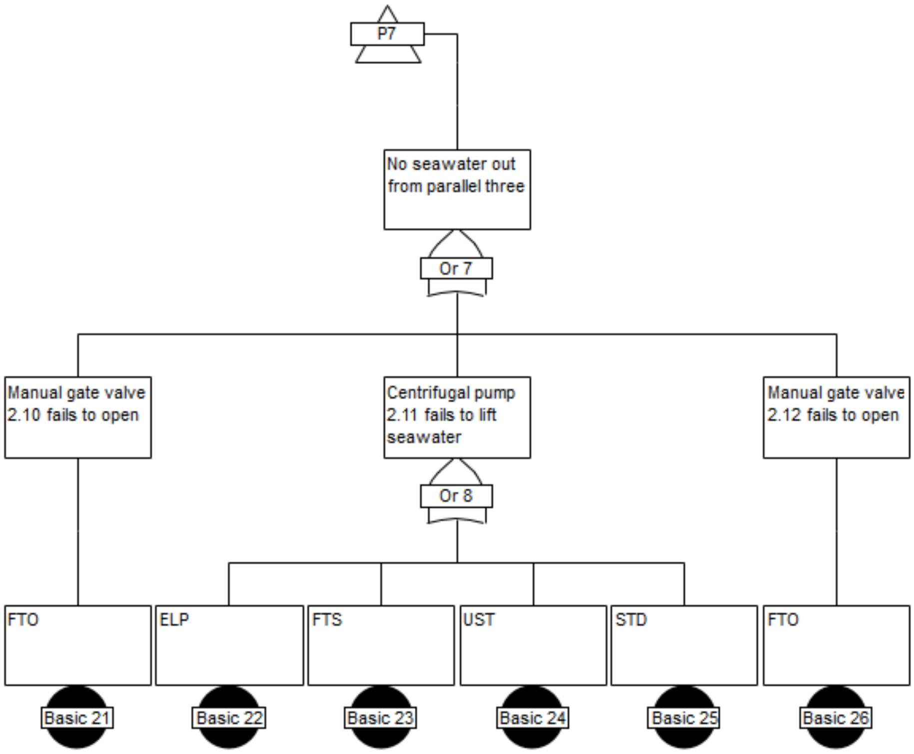
Figure N.1: Fault tree two, No seawater to scrubber device and venturi

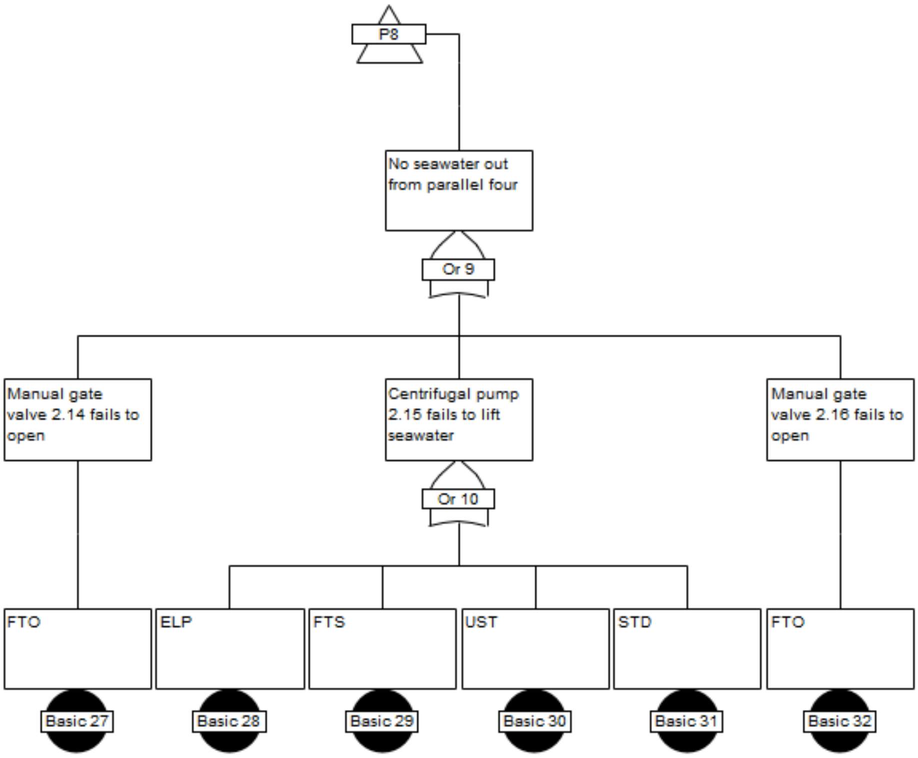

P2
No seawater access scrubbing water supply pump inlet
And 1
Pipeline 2.23 damaged
Inlet monitor system fails to function
Or 2
ELP
Basic 3
Manual gate valve 1.2 fails to open
Manual gate valve 1.3 fails to open
Electronics and sensing element in inlet monitor 1.1 fails to function
KooN 1
2/3
FTO
FTO
AOL
FTF
SPO
Basic 4
Basic 5
Basic 6
Basic 7
Basic 8

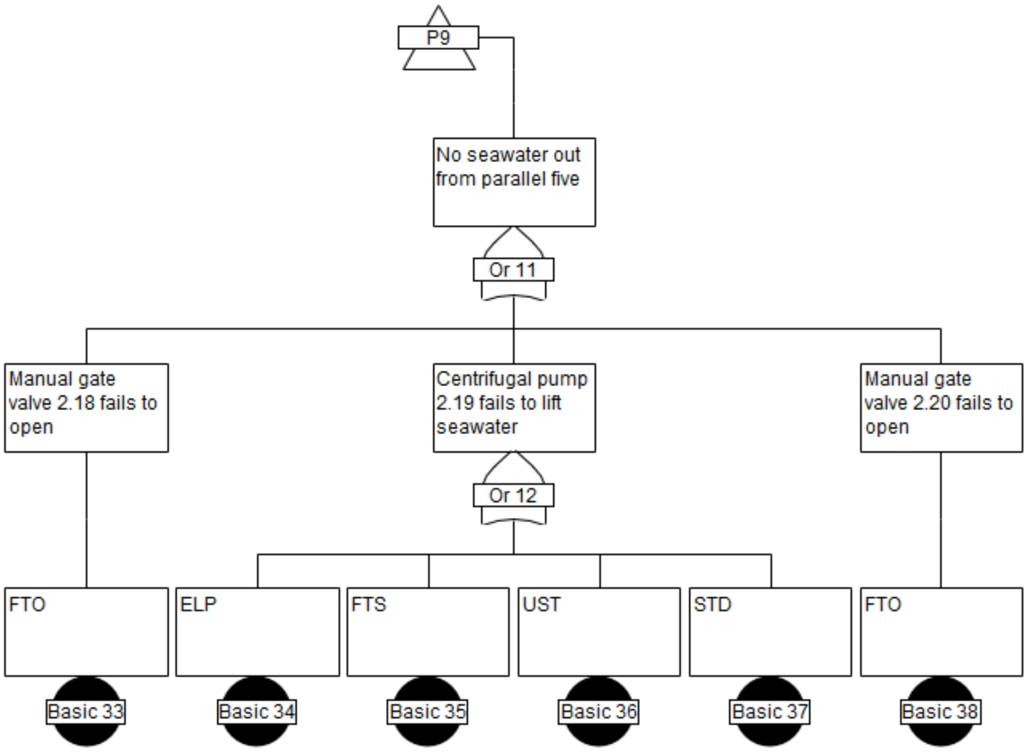

P3
Scrubbing water supply pump inlet fails to function
KooN 2
3/5
No seawater out from parallel one
No seawater out from parallel two
No seawater out from parallel three
No seawater out from parallel four
No seawater out from parallel five
P5
P6
P7
P8
P9

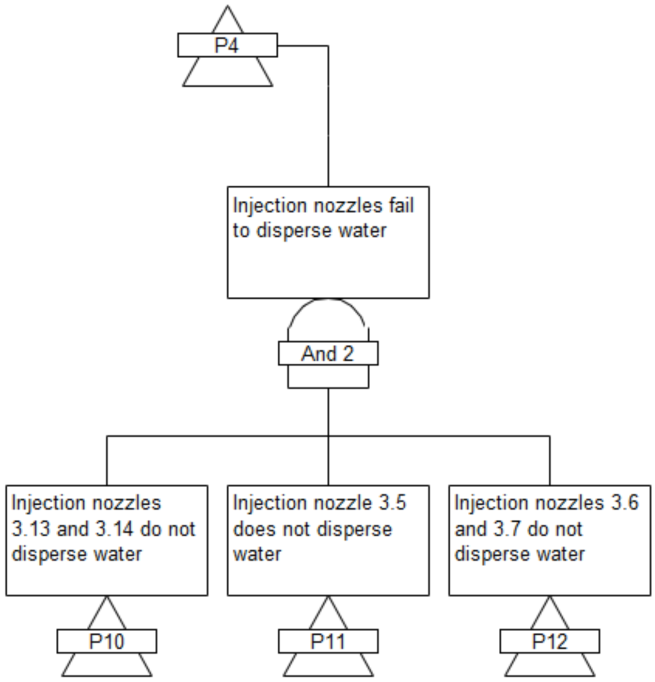

P5
No seawater out from parallel one
Or 3
Manual gate valve 2.2 fails to open
Centrifugal pump 2.3 fails to lift seawater
Manual gate valve 2.4 fails to open
Or 4
FTO
ELP
FTS
UST
STD
FTO
Basic 9
Basic 10
Basic 11
Basic 12
Basic 13
Basic 14

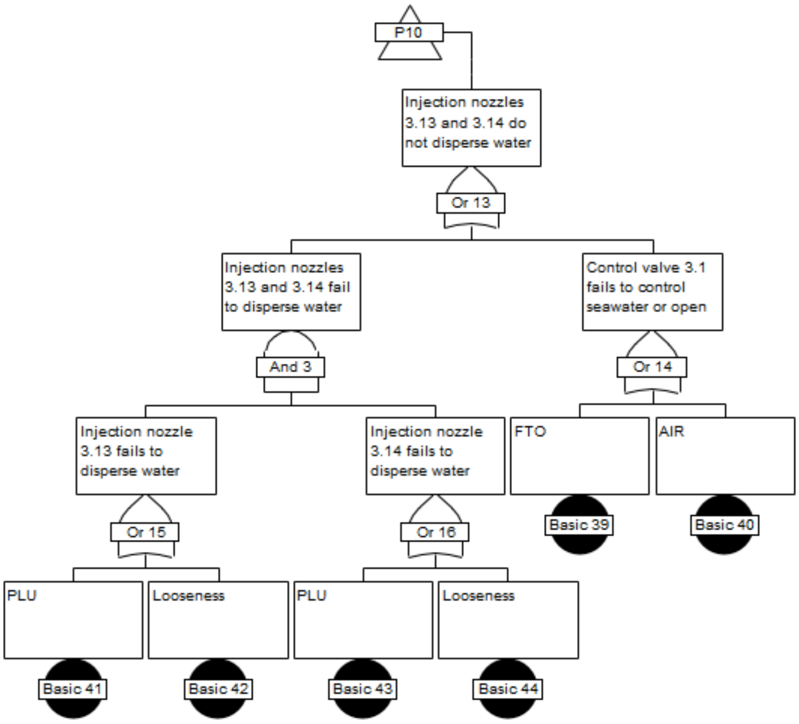

P6
No seawater out from parallel two
Or 5
Manual gate valve 2.6 fails to open
Centrifugal pump 2.7 fails to lift seawater
Manual gate valve 2.8 fails to open
Or 6
FTO
ELP
FTS
UST
STD
FTO
Basic 15
Basic 16
Basic 17
Basic 18
Basic 19
Basic 20

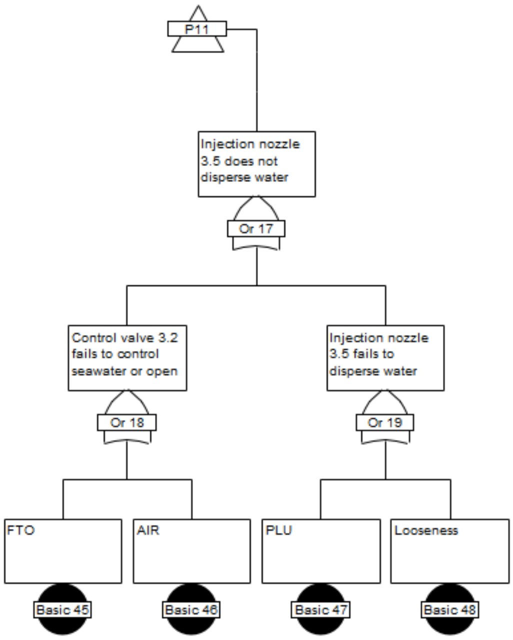

P7
No seawater out from parallel three
Or 7
Manual gate valve 2.10 fails to open
Centrifugal pump 2.11 fails to lift seawater
Manual gate valve 2.12 fails to open
Or 8
FTO
ELP
FTS
UST
STD
FTO
Basic 21
Basic 22
Basic 23
Basic 24
Basic 25
Basic 26

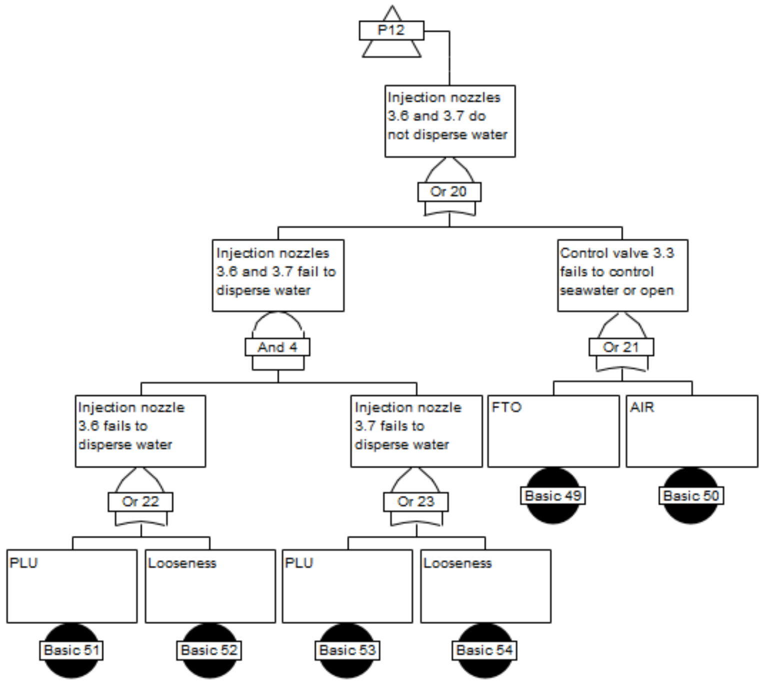

P8
No seawater out from parallel four
Or 9
Manual gate valve 2.14 fails to open
Centrifugal pump 2.15 fails to lift seawater
Manual gate valve 2.16 fails to open
Or 10
FTO
ELP
FTS
UST
STD
FTO
Basic 27
Basic 28
Basic 29
Basic 30
Basic 31
Basic 32


P9
No seawater out from parallel five
Or 11
Manual gate valve 2.18 fails to open
Centrifugal pump 2.19 fails to lift seawater
Manual gate valve 2.20 fails to open
Or 12
FTO
ELP
FTS
UST
STD
FTO
Basic 33
Basic 34
Basic 35
Basic 36
Basic 37
Basic 38


P4
Injection nozzles fail to disperse water
And 2
Injection nozzles 3.13 and 3.14 do not disperse water
Injection nozzle 3.5 does not disperse water
Injection nozzles 3.6 and 3.7 do not disperse water
P10
P11
P12


P10
Injection nozzles 3.13 and 3.14 do not disperse water
Or 13
Injection nozzles 3.13 and 3.14 fail to disperse water
And 3
Control valve 3.1 fails to control seawater or open
Or 14
Injection nozzle 3.13 fails to disperse water
Or 15
Injection nozzle 3.14 fails to disperse water
Or 16
FTO
AIR
Basic 39
Basic 40
PLU
Looseness
PLU
Looseness
Basic 41
Basic 42
Basic 43
Basic 44


P11
Injection nozzle 3.5 does not disperse water
Or 17
Control valve 3.2 fails to control seawater or open
Or 18
Injection nozzle 3.5 fails to disperse water
Or 19
FTO
AIR
PLU
Looseness
Basic 45
Basic 46
Basic 47
Basic 48


P12
Injection nozzles 3.6 and 3.7 do not disperse water
Or 20
Injection nozzles 3.6 and 3.7 fail to disperse water
And 4
Control valve 3.3 fails to control seawater or open
Or 21
Injection nozzle 3.6 fails to disperse water
Or 22
Injection nozzle 3.7 fails to disperse water
Or 23
FTO
Basic 49
AIR
Basic 50
PLU
Basic 51
Looseness
Basic 52
PLU
Basic 53
Looseness
Basic 54

O. F3: INLET MONITOR DOESN'T MEASURE PH, PAH, TURBIDITY & TEMPERATURE

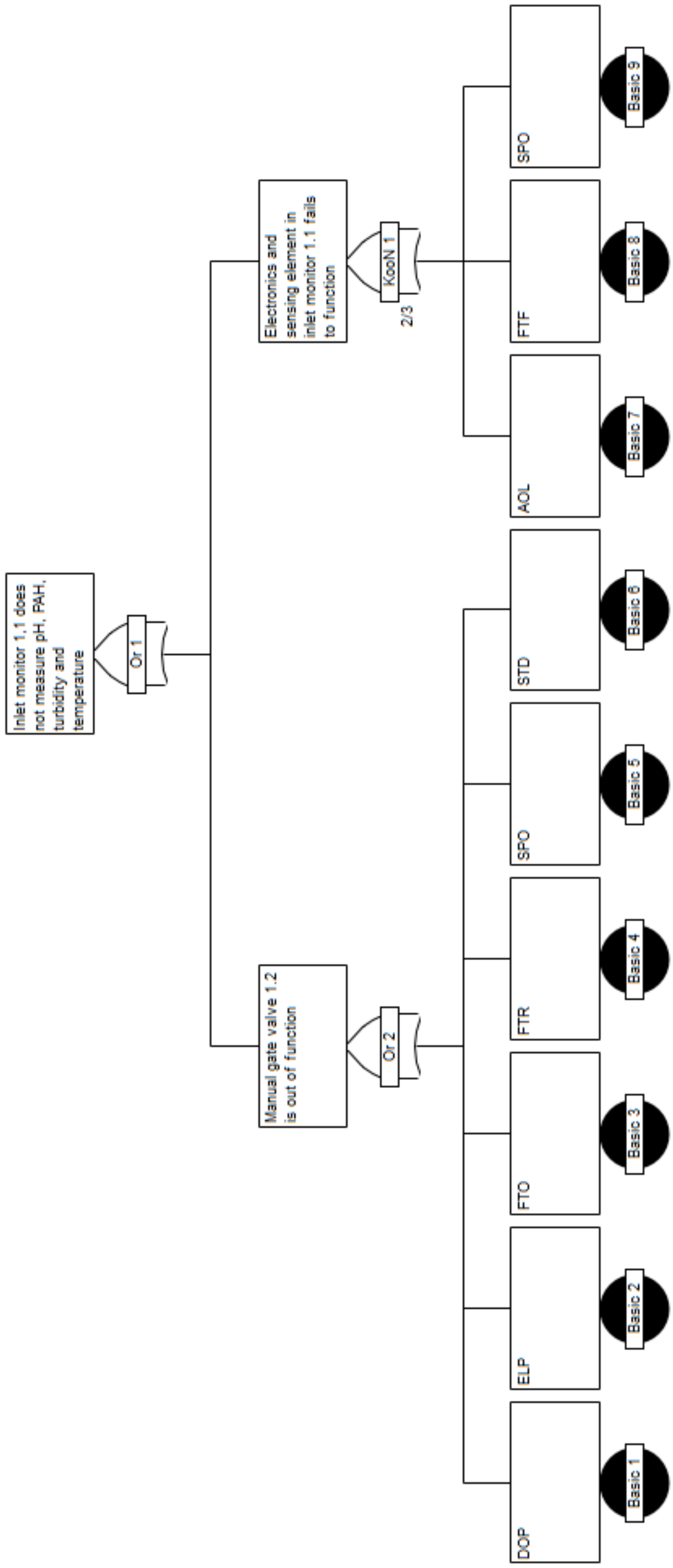


Figure O.1: Fault tree three, Inlet monitor doesn‘t measure pH, PAH, turbidity & temperature

P. F4: Outlet Monitor doesn't Measure pH, PAH, Turbidity & Temperature

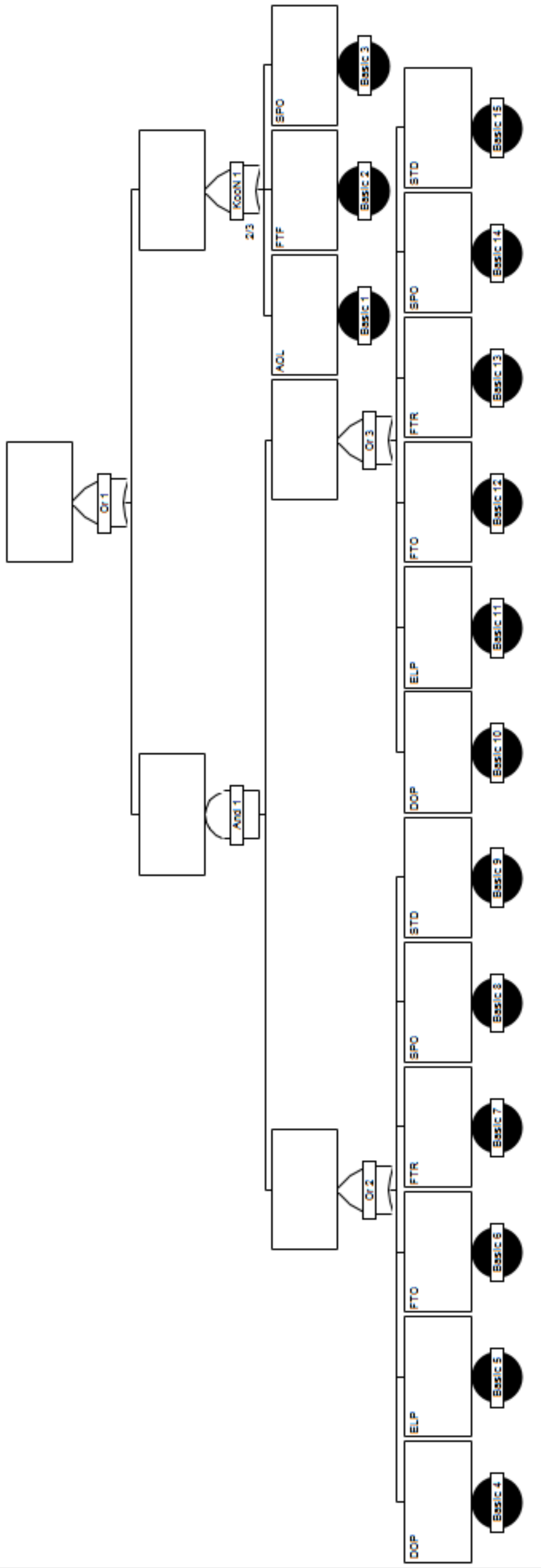


Figure P.1: Fault tree four, Outlet monitor doesn't measure pH, PAH, turbidity & temperature

Q. F5: WASHWATER NOT PURIFIED

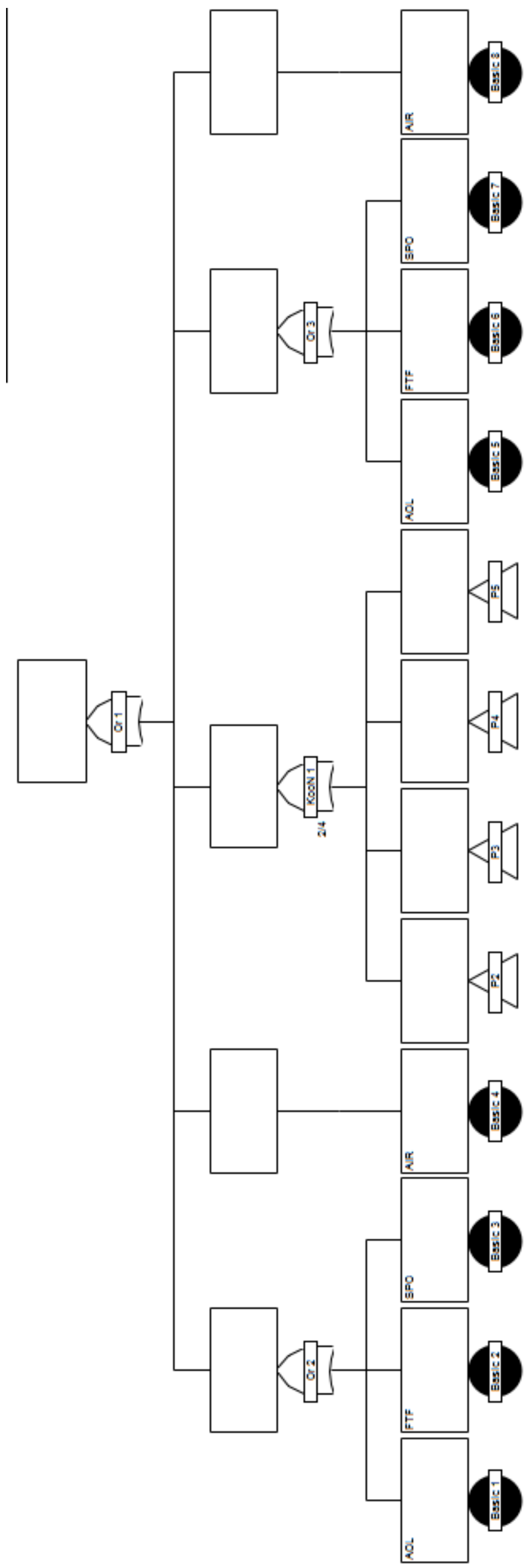
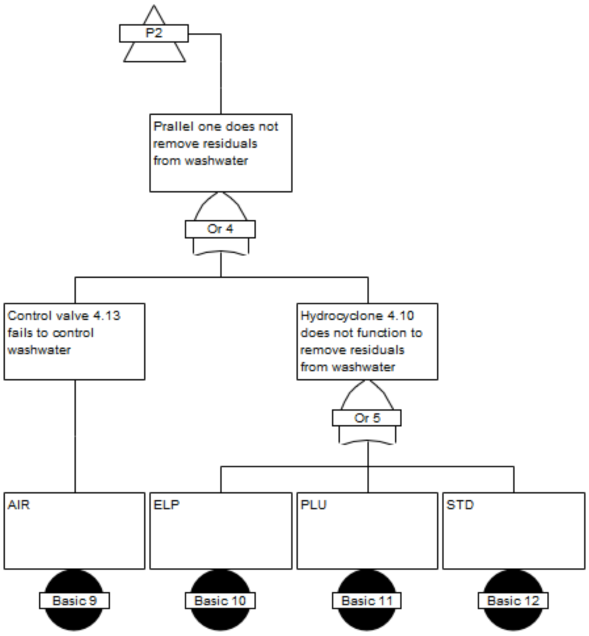
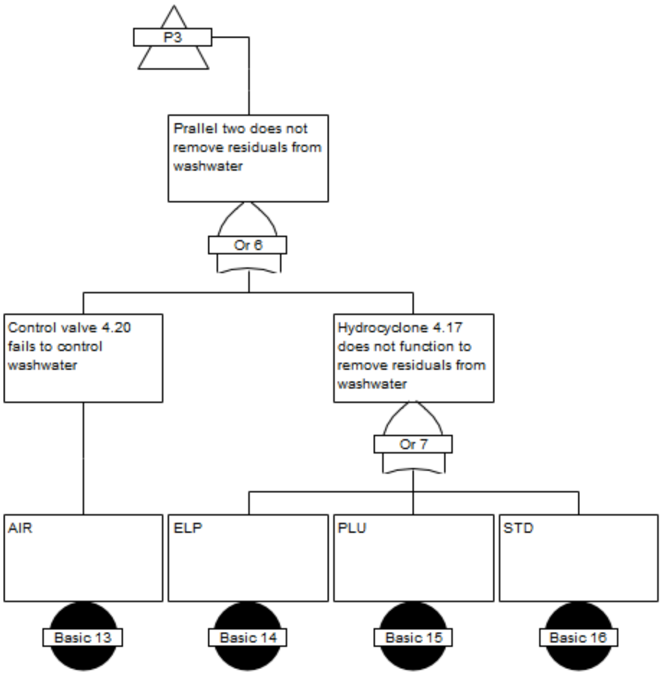
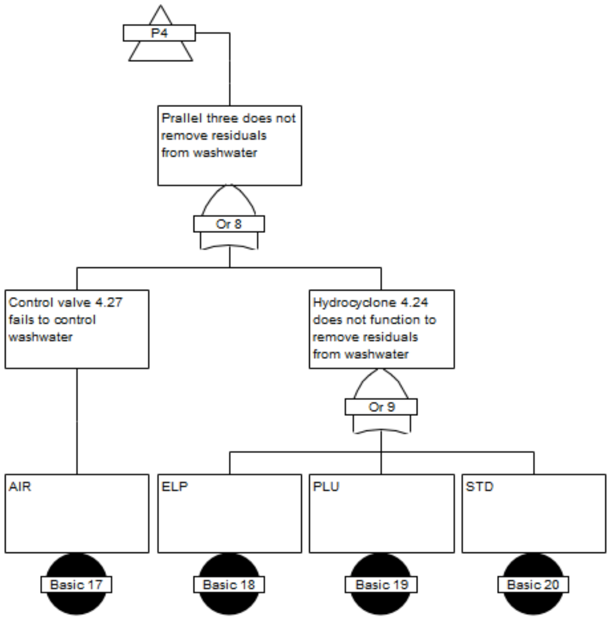
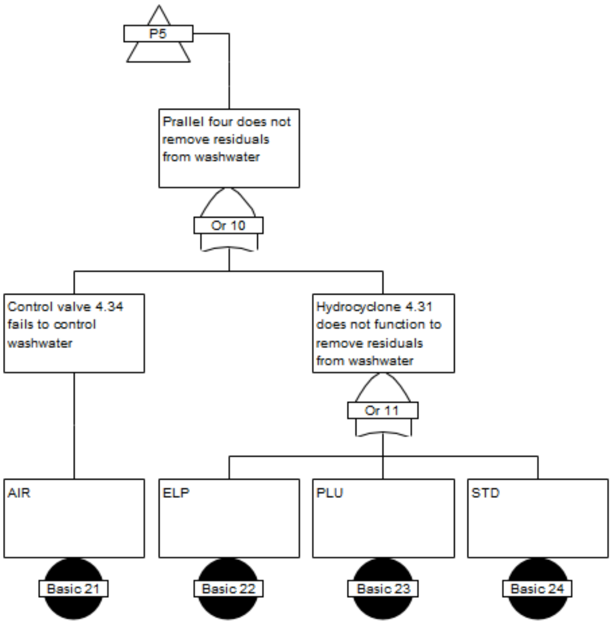


Figure Q.1: Fault tree five, Washwater not purified


P2
Prallel one does not remove residuals from washwater
Or 4
Control valve 4.13 fails to control washwater
Hydrocyclone 4.10 does not function to remove residuals from washwater
Or 5
AIR
ELP
PLU
STD
Basic 9
Basic 10
Basic 11
Basic 12


P3
Prallel two does not remove residuals from washwater
Or 6
Control valve 4.20 fails to control washwater
Hydrocyclone 4.17 does not function to remove residuals from washwater
Or 7
AIR
ELP
PLU
STD
Basic 13
Basic 14
Basic 15
Basic 16


P4
Prallel three does not remove residuals from washwater
Or 8
Control valve 4.27 fails to control washwater
Hydrocyclone 4.24 does not function to remove residuals from washwater
Or 9
AIR
ELP
PLU
STD
Basic 17
Basic 18
Basic 19
Basic 20


P5
Prallel four does not remove residuals from washwater
Or 10
Control valve 4.34 fails to control washwater
Hydrocyclone 4.31 does not function to remove residuals from washwater
Or 11
AIR
ELP
PLU
STD
Basic 21
Basic 22
Basic 23
Basic 24

R. F6: Exhaust Gas not Washed in Scrubber Device

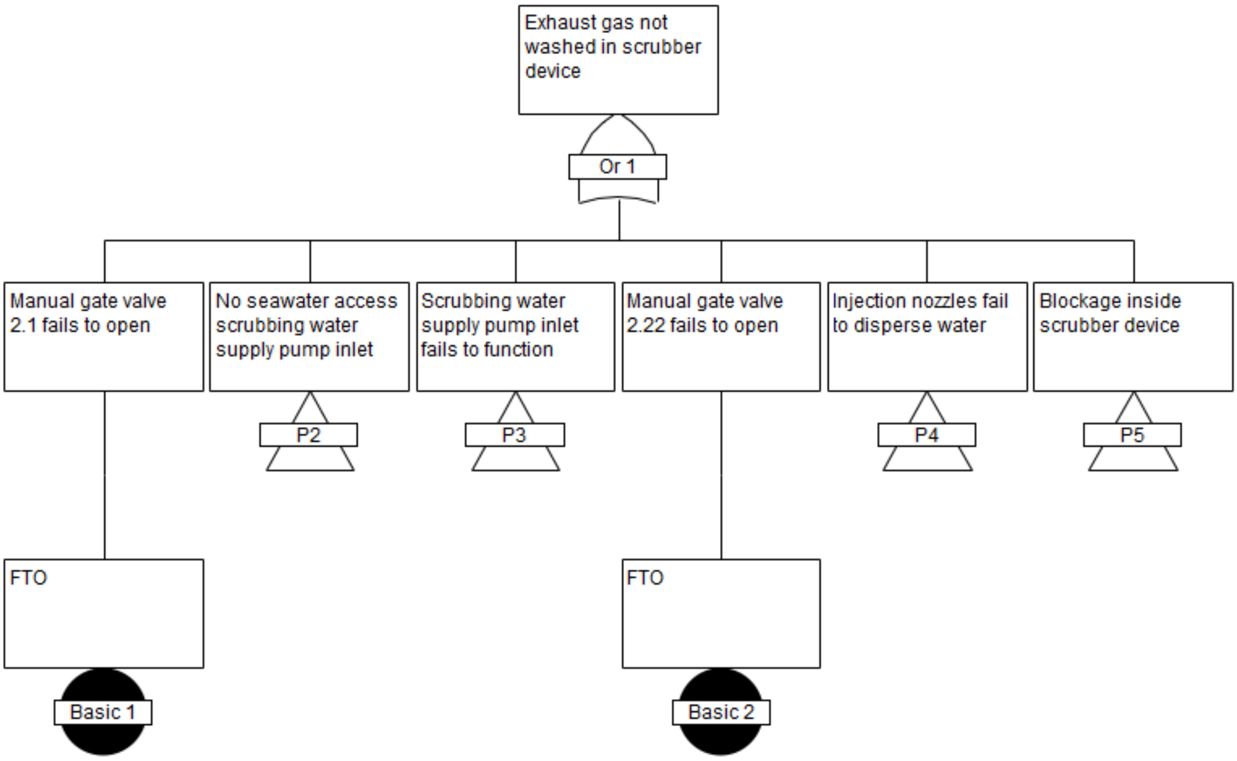
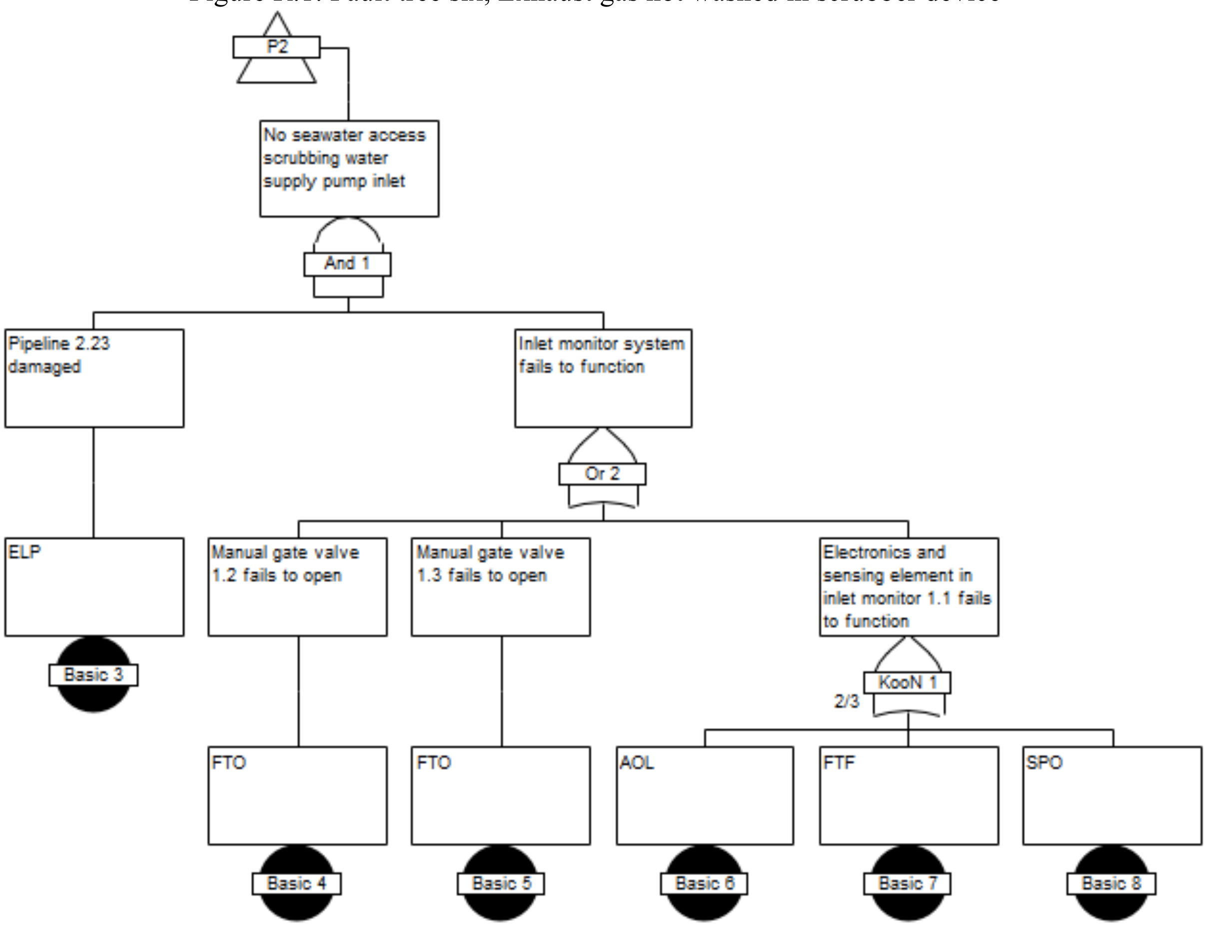
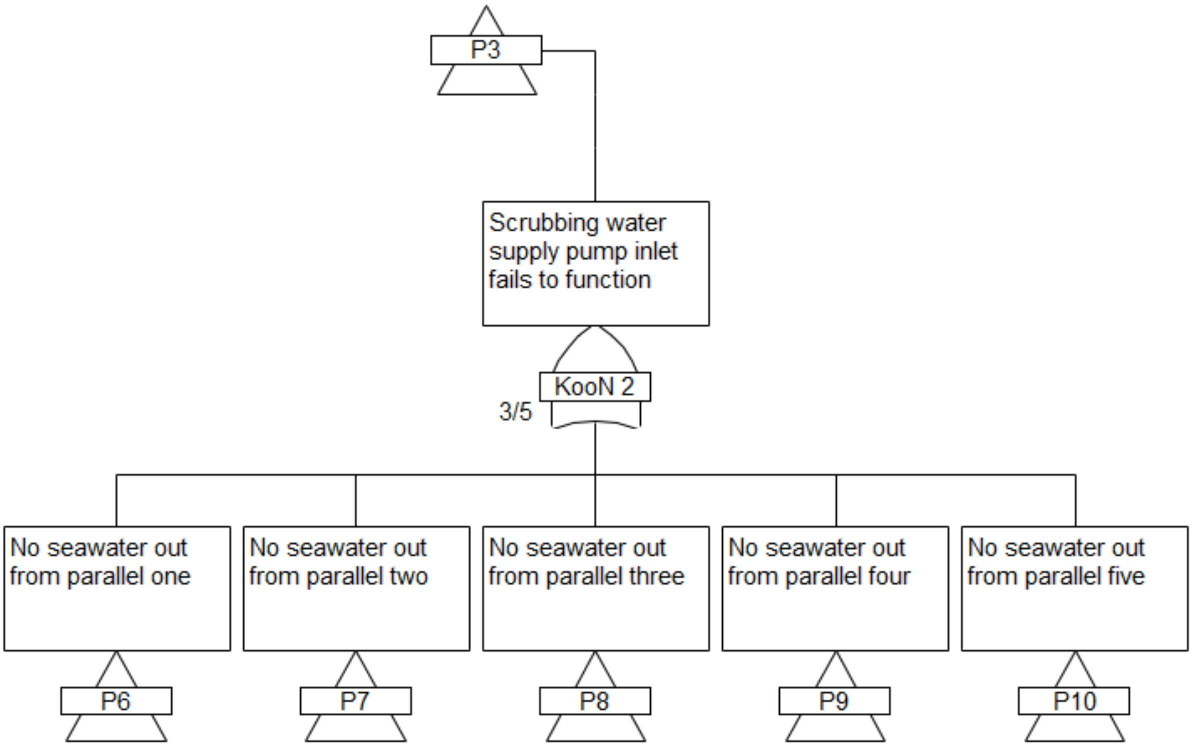
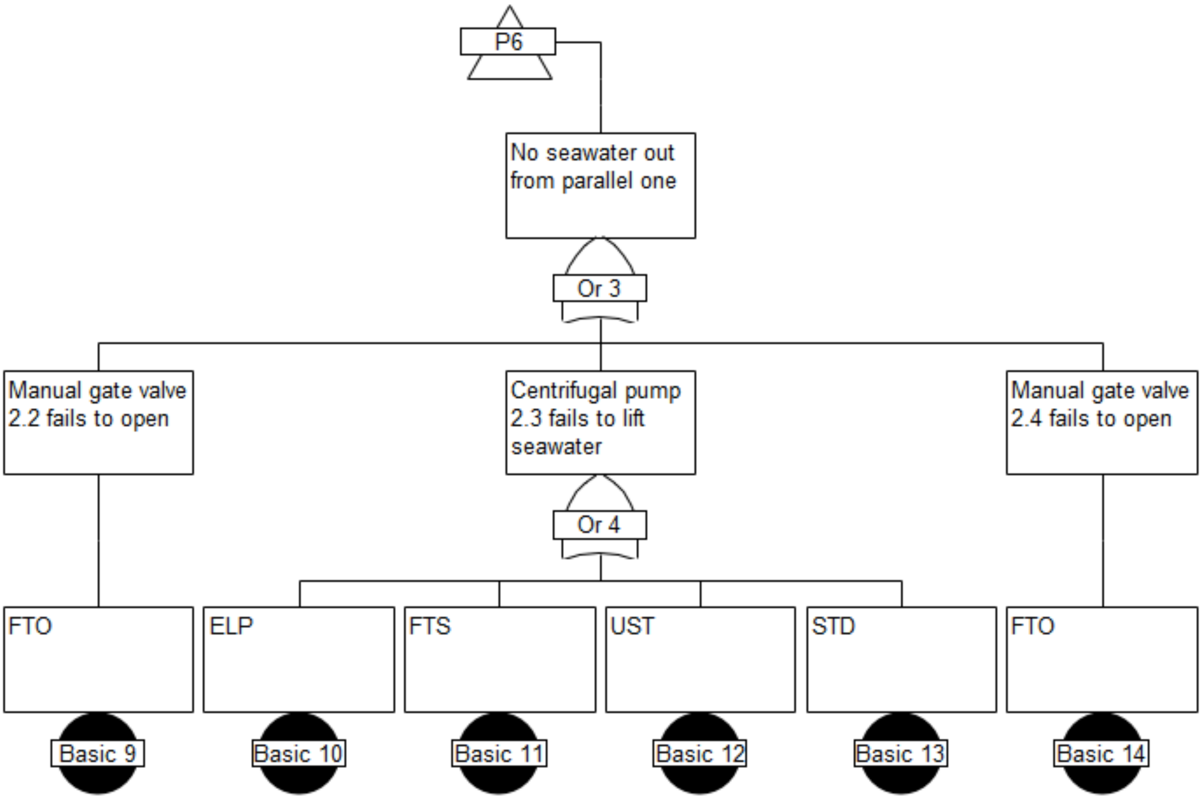
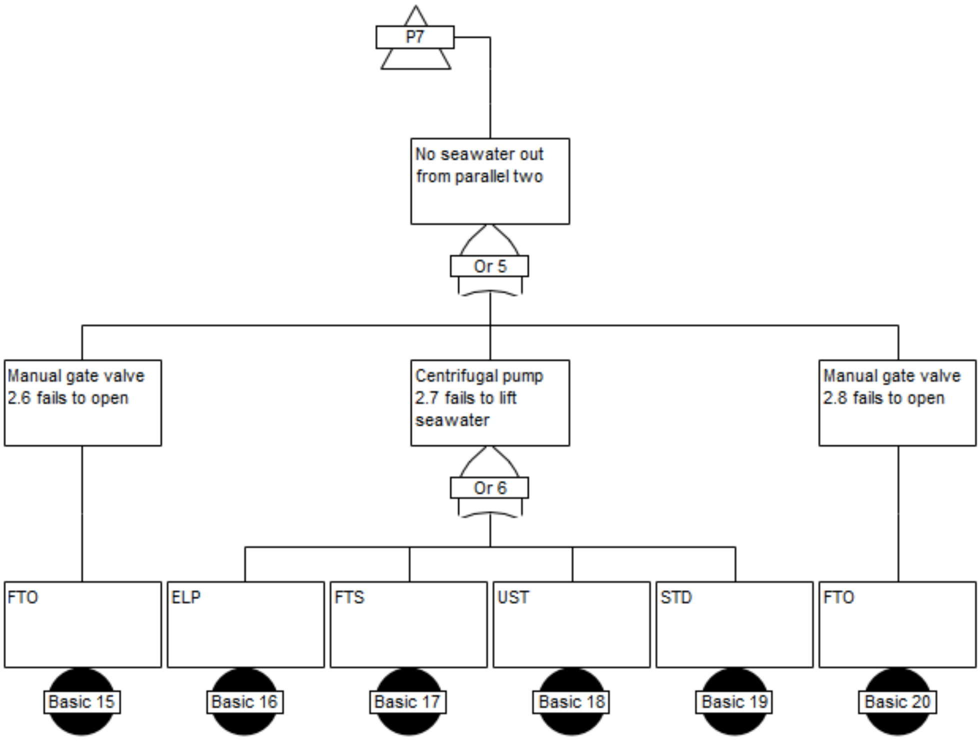


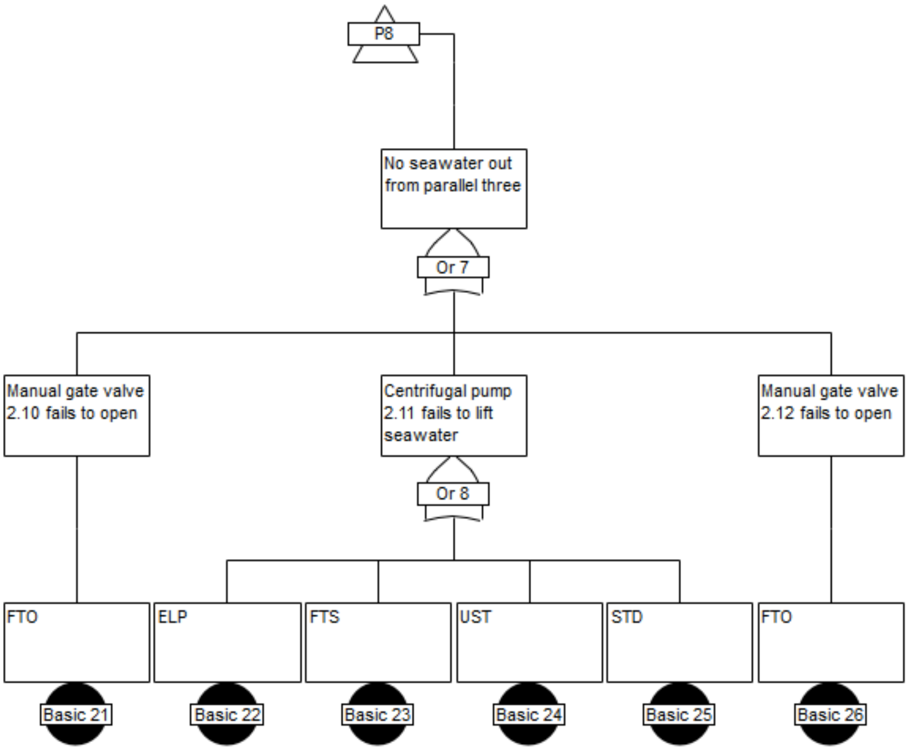
Figure R.1: Fault tree six, Exhaust gas not washed in scrubber device

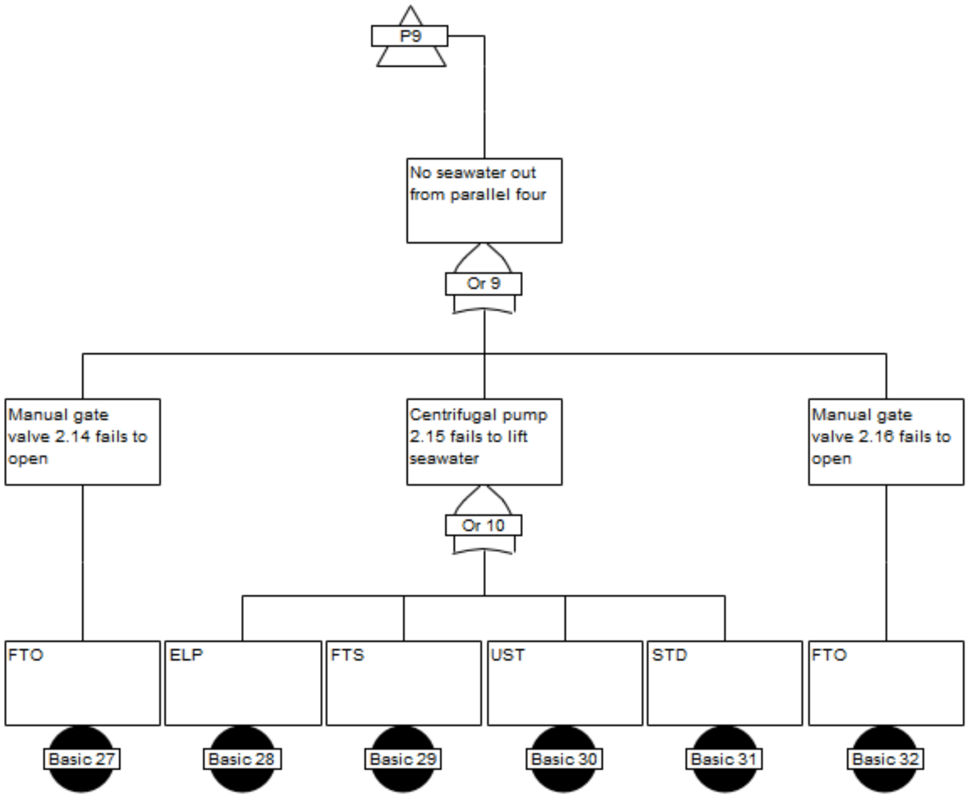


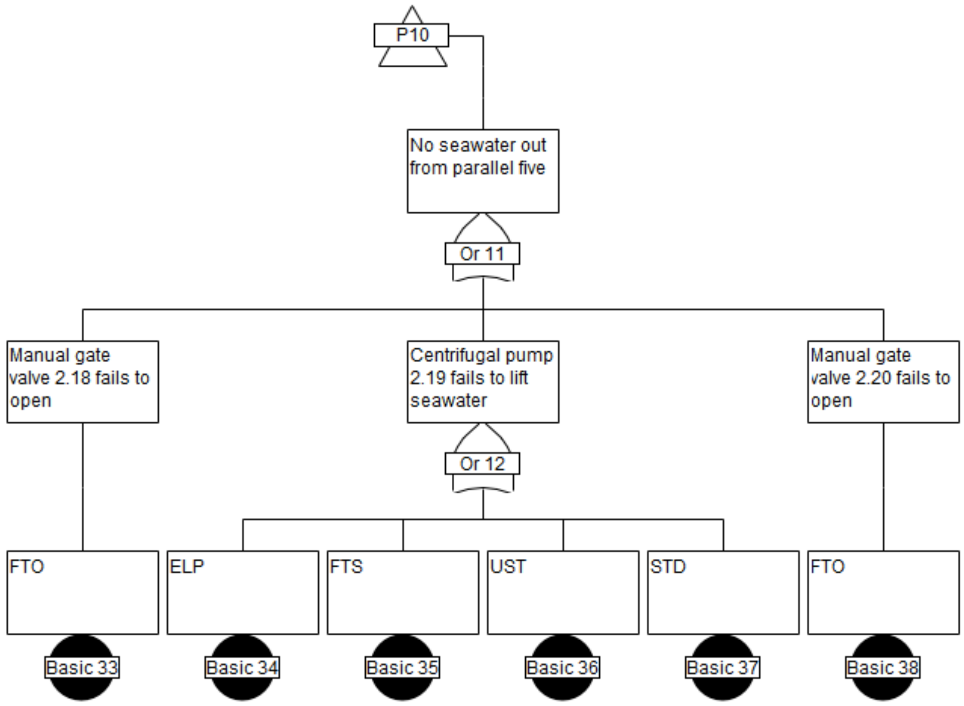

P3
Scrubbing water supply pump inlet fails to function
KooN 2
3/5
No seawater out from parallel one
No seawater out from parallel two
No seawater out from parallel three
No seawater out from parallel four
No seawater out from parallel five
P6
P7
P8
P9
P10

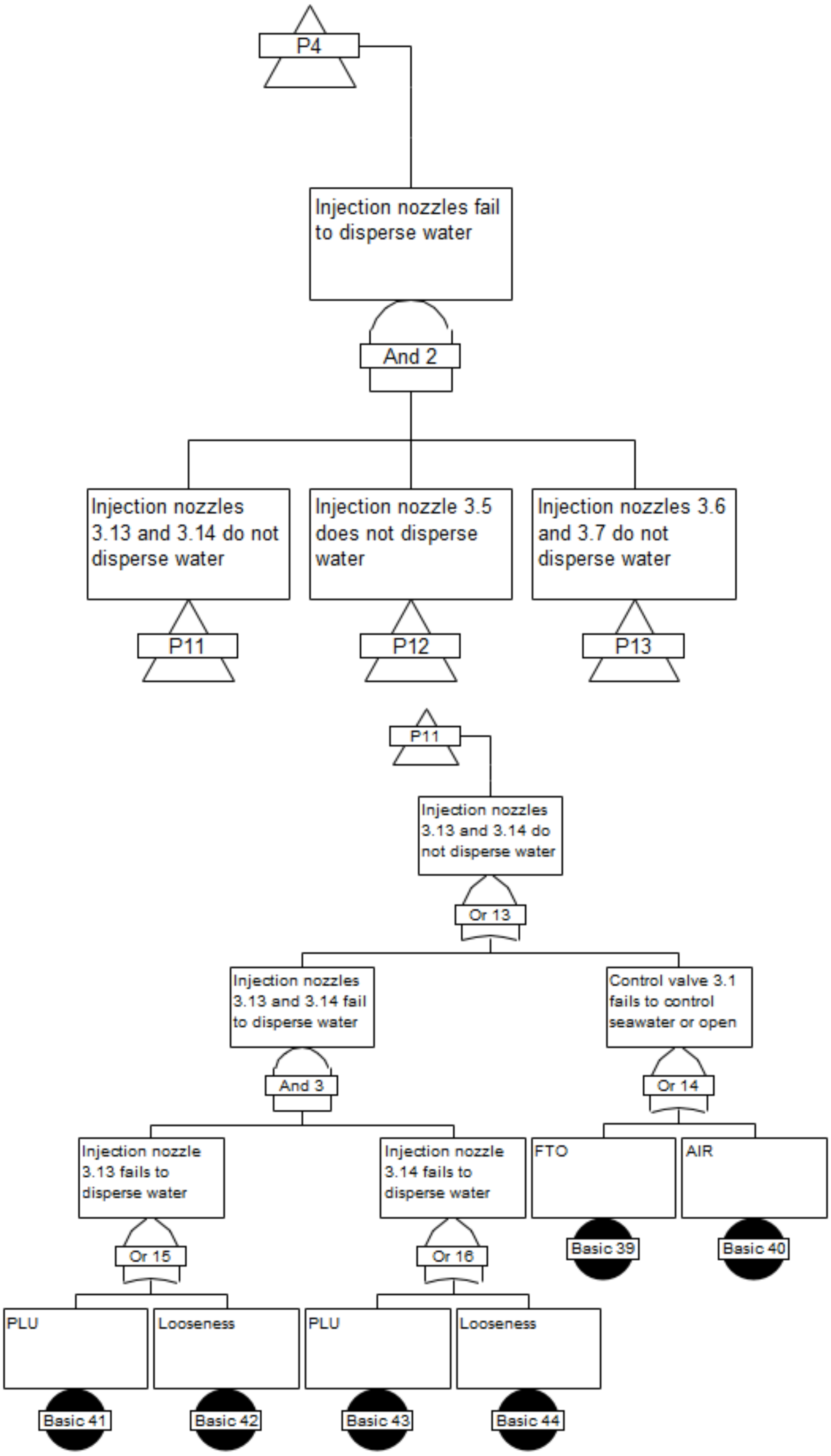

P6
No seawater out from parallel one
Or 3
Manual gate valve 2.2 fails to open
Centrifugal pump 2.3 fails to lift seawater
Manual gate valve 2.4 fails to open
Or 4
FTO
ELP
FTS
UST
STD
FTO
Basic 9
Basic 10
Basic 11
Basic 12
Basic 13
Basic 14

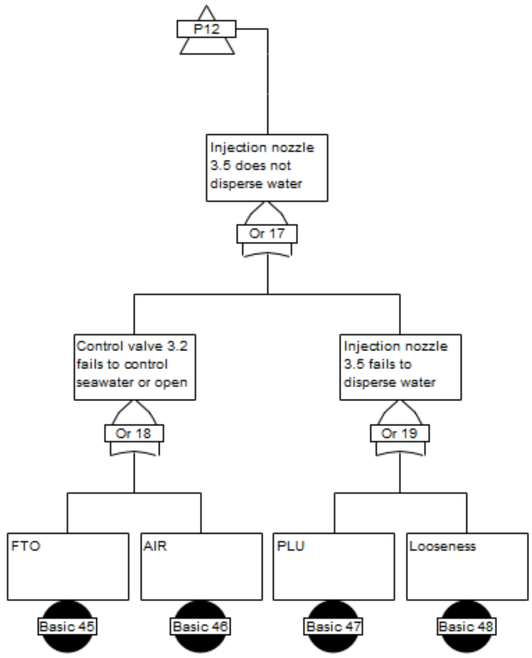

P7
No seawater out from parallel two
Or 5
Manual gate valve 2.6 fails to open
Centrifugal pump 2.7 fails to lift seawater
Manual gate valve 2.8 fails to open
Or 6
FTO
ELP
FTS
UST
STD
FTO
Basic 15
Basic 16
Basic 17
Basic 18
Basic 19
Basic 20

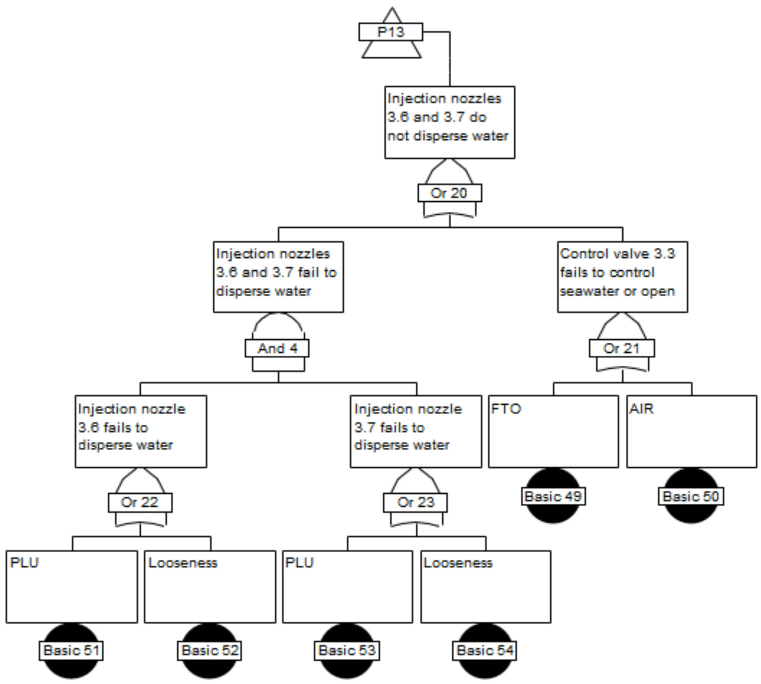

P8
No seawater out from parallel three
Or 7
Manual gate valve 2.10 fails to open
Centrifugal pump 2.11 fails to lift seawater
Manual gate valve 2.12 fails to open
Or 8
FTO
ELP
FTS
UST
STD
FTO
Basic 21
Basic 22
Basic 23
Basic 24
Basic 25
Basic 26

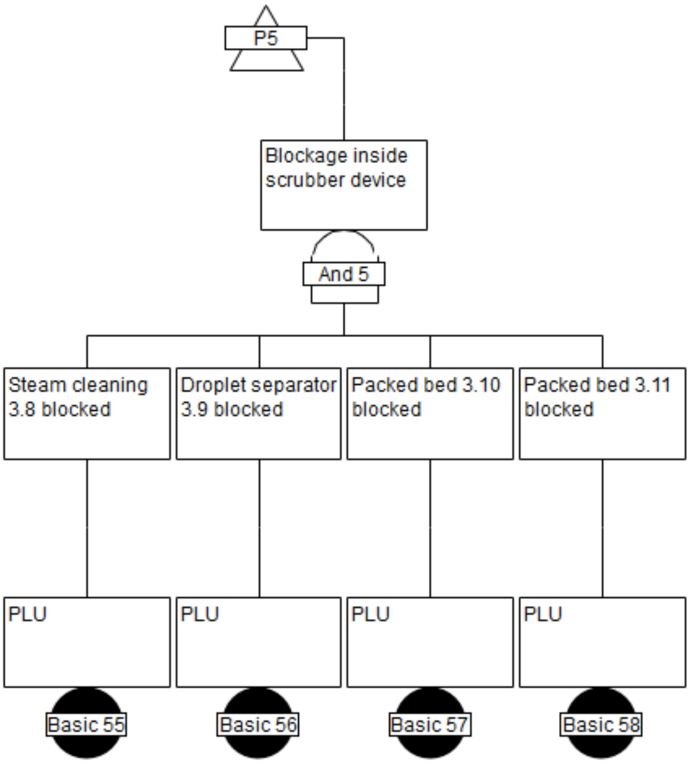

P9
No seawater out from parallel four
Or 9
Manual gate valve 2.14 fails to open
Centrifugal pump 2.15 fails to lift seawater
Manual gate valve 2.16 fails to open
Or 10
FTO
ELP
FTS
UST
STD
FTO
Basic 27
Basic 28
Basic 29
Basic 30
Basic 31
Basic 32


P10
No seawater out from parallel five
Or 11
Manual gate valve 2.18 fails to open
Centrifugal pump 2.19 fails to lift seawater
Manual gate valve 2.20 fails to open
Or 12
FTO
ELP
FTS
UST
STD
FTO
Basic 33
Basic 34
Basic 35
Basic 36
Basic 37
Basic 38


P4
Injection nozzles fail to disperse water
And 2
Injection nozzles 3.13 and 3.14 do not disperse water
Injection nozzle 3.5 does not disperse water
Injection nozzles 3.6 and 3.7 do not disperse water
P11
P12
P13
P11
Injection nozzles 3.13 and 3.14 do not disperse water
Or 13
Injection nozzles 3.13 and 3.14 fail to disperse water
Control valve 3.1 fails to control seawater or open
And 3
Or 14
Injection nozzle 3.13 fails to disperse water
Injection nozzle 3.14 fails to disperse water
FTO
AIR
Basic 39
Basic 40
Or 15
Or 16
PLU
Looseness
PLU
Looseness
Basic 41
Basic 42
Basic 43
Basic 44


P12
Injection nozzle 3.5 does not disperse water
Or 17
Control valve 3.2 fails to control seawater or open
Injection nozzle 3.5 fails to disperse water
Or 18
Or 19
FTO
AIR
PLU
Looseness
Basic 45
Basic 46
Basic 47
Basic 48


P13
Injection nozzles 3.6 and 3.7 do not disperse water
Or 20
Injection nozzles 3.6 and 3.7 fail to disperse water
Control valve 3.3 fails to control seawater or open
And 4
Or 21
Injection nozzle 3.6 fails to disperse water
Injection nozzle 3.7 fails to disperse water
FTO
AIR
Basic 49
Basic 50
Or 22
Or 23
PLU
Looseness
PLU
Looseness
Basic 51
Basic 52
Basic 53
Basic 54


P5
Blockage inside scrubber device
And 5
Steam cleaning 3.8 blocked
Droplet separator 3.9 blocked
Packed bed 3.10 blocked
Packed bed 3.11 blocked
PLU
PLU
PLU
PLU
Basic 55
Basic 56
Basic 57
Basic 58

S. Event Tree, Overpressure

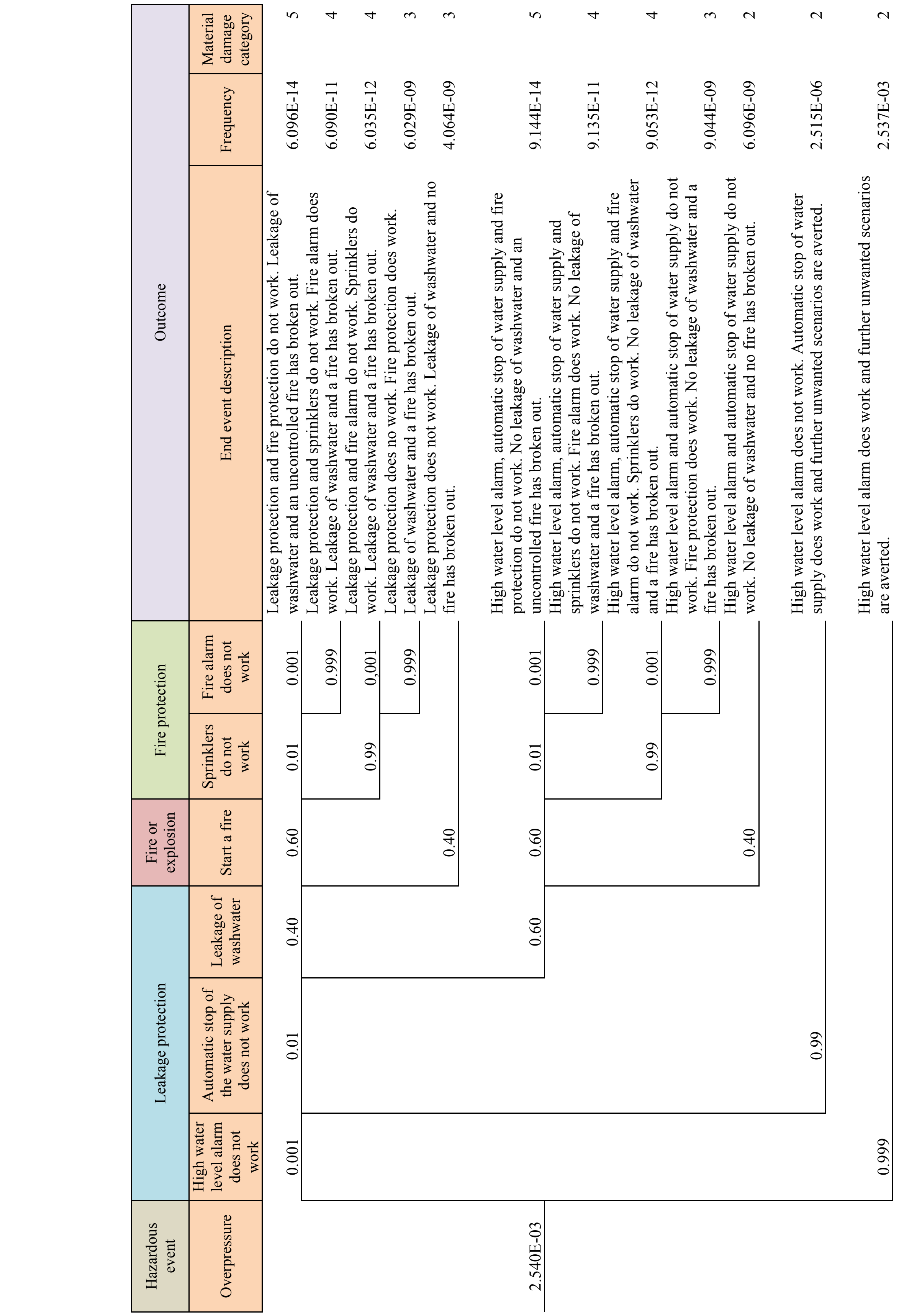


Figure S.1: Event tree one, Overpressure

T. Event Tree, Hazards Related to Loading/Discharging

Hazardous event	Electrical power protection			Automation and control system		Outcome		
Hazards related to loading/discharging	Separate generator does not work	Switchboard does not work	Local starter does not work	Scrubber alarm does not work	Control panel does not work	End event description	Frequency	Material damage category
2.100E-05	0.01	0.001	0.01	0.001	0.001	Electrical power protection and automation and control system do not work.	2.100E-18	4
					0.999	Electrical power protection and scrubber alarm do not work. Control panel in engine room does work.	2.098E-15	4
				0.999	0.001	Electrical power protection and control panel do not work. Scrubber alarm do work.	2.098E-15	4
					0.999	Electrical power protection does not work. Automation and control system does work.	2.096E-12	3
			0.99	0.001	0.001	Separate generator, switchboard, scrubber alarm, and control panel do not work. Local starter does work.	2.079E-16	3
					0.999	Separate generator, switchboard, and scrubber alarm do not work. Local starter and control panel do work.	2.077E-13	3
				0.999	0.001	Separate generator, switchboard, and control panel do not work. Local starter and scrubber alarm do work.	2.077E-13	3
					0.999	Separate generator and switchboard do not work. Local starter, scrubber alarm, and control panel do work.	2.075E-10	3
		0.999	0.01	0.001	0.001	Separate generator, local starter, scrubber alarm, and control panel do not work. Switchboard does work.	2.098E-15	3
					0.999	Separate generator, local starter, and scrubber alarm do not work. Switchboard and control panel do work.	2.096E-12	3
				0.999	0.001	Separate generator, local starter, and control panel do not work. Switchboard and scrubber alarm do work.	2.096E-12	3
					0.999	Separate generator and local starter do not work. Switchboard, scrubber alarm, and control panel do work.	2.094E-09	2
			0.99	0.001	0.001	Separate generator, scrubber alarm, and control panel do not work. Switchboard and local starter do work.	2.077E-13	3
					0.999	Separate generator and scrubber alarm do not work. Switchboard, local starter, and control panel do work.	2.075E-10	2
				0.999	0.001	Separate generator and control panel do not work. Switchboard, local starter, and scrubber alarm do work.	2.075E-10	2
					0.999	Separate generator does not work. Switchboard, local starter, scrubber alarm and control panel do work.	2.073E-07	2
	0.99					Separate generator does work and further unwanted scenarios are averted.	2.079E-05	1

Figure T.1: Event tree two, Hazards related to loading/discharging

U. Event Tree, Purification Failure

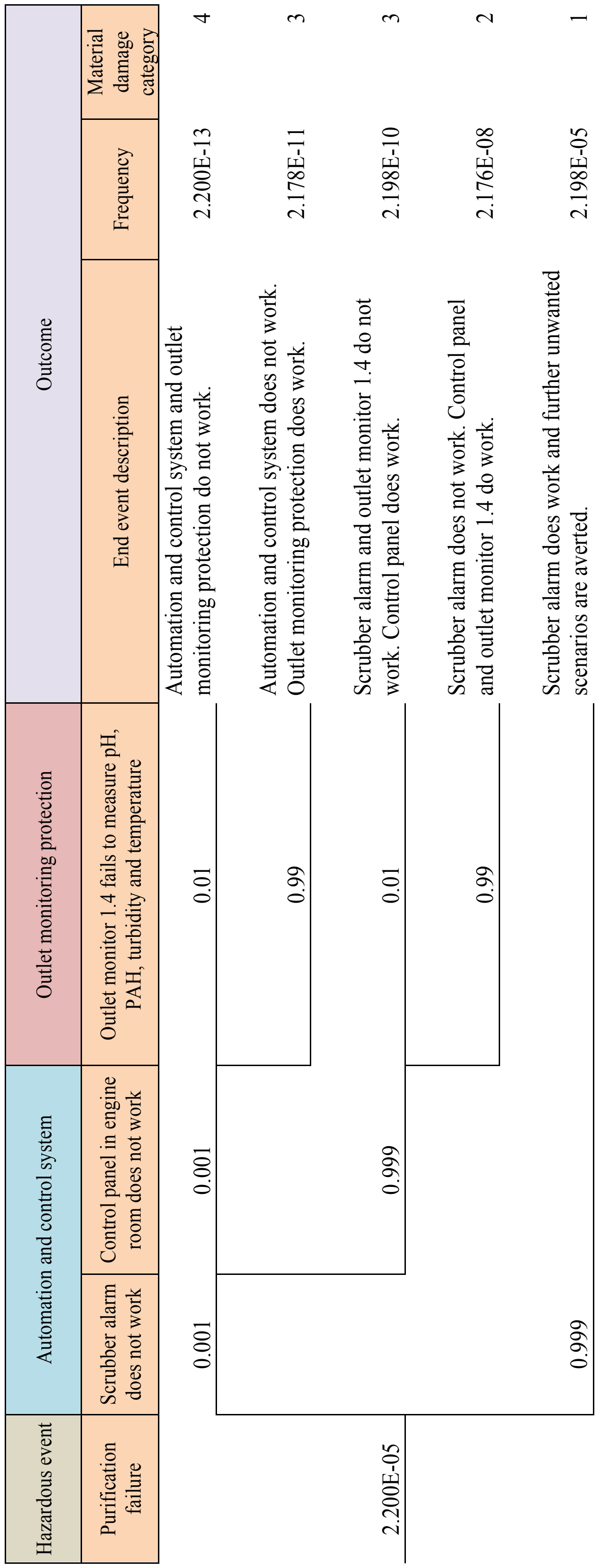


Figure U.1: Even tree three, Purification failure

V. RISK CONTRIBUTION TREE

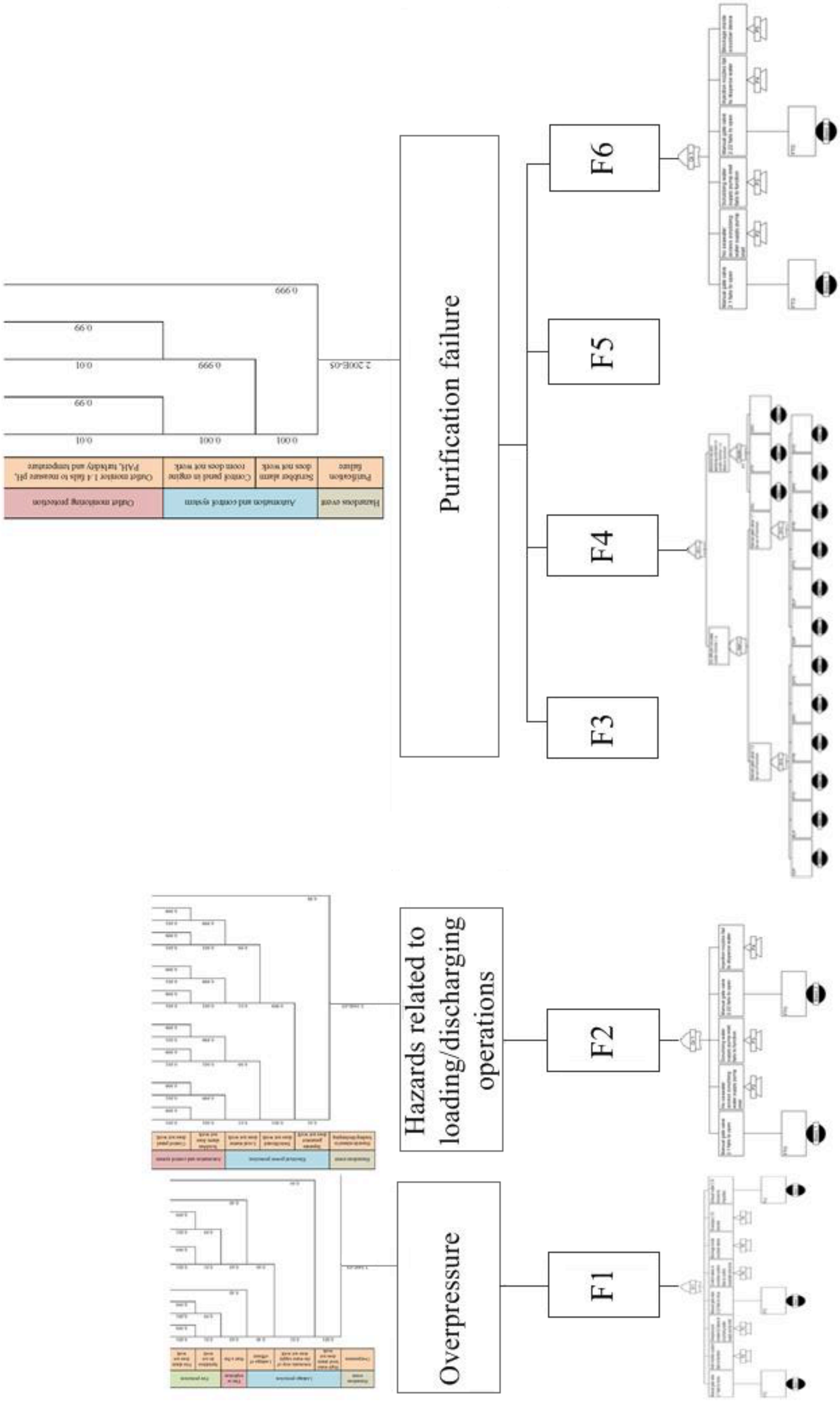


Figure V.1: Risk Contribution Tree (RCT)

W. TOTAL COSTS OF RISK CONTROL OPTIONS

Table W.1: Total cost of risk control option one

	CAPEX/OPEX		Cost of RCO through 25 years	
RCO 1 Cost	Low	High	Low	High
Investment/purchase	$37 950,00	$556 600,00	$5 060 020,37	$74 213 632,07
Training	$7 590,00	$111 320,00	$1 012 004,07	$14 842 726,41
Total			$6 072 024,44	$89 056 358,49

Table W.2: Total cost of risk control option two

	CAPEX/OPEX		Cost of RCO through 25 years	
RCO 2 Cost	Low	High	Low	High
Investment/purchase	$37 950,00	$556 600,00	$5 060 020,37	$74 213 632,07
Maintenance	$11 385,00	$222 640,00	$1 518 006,11	$29 685 452,83
Training	$7 590,00	$111 320,00	$1 012 004,07	$14 842 726,41
Total costs			$7 590 030,55	$118 741 811,32

Table W.3: Total cost of risk control option three

	CAPEX/OPEX		Cost of RCO through 25 years	
RCO 3 Cost	Low	High	Low	High
Downtime	$265 650,00	$5 009 400,00	$1 328 250,00	$25 047 000,00
Installation and commissioning	$56 925,00	$1 391 500,00	$284 625,00	$6 957 500,00
Investment/purchase	$151 800,00	$2 226 400,00	$759 000,00	$11 132 000,00
Total costs			$2 371 875,00	$43 136 500,00

Table W.4: Total cost of risk control option four

	CAPEX/OPEX		Cost of RCO through 25 years	
RCO 4 Cost	Low	High	Low	High
Downtime	$151 800,00	$2 783 000,00	$151 800,00	$2 783 000,00
Investment/purchase	$37 950,00	$556 600,00	$37 950,00	$556 600,00
Total costs			$189 750,00	$3 339 600,00