Safety Assessment for Oil Tankers and Container Vessels Focused on Fire and Explosion In the Machinery Space

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Abstract

A considerable part of world merchandise is transported by sea, and with about 150,000 crew members working on the ship types of interest for this thesis there is much at stake if an accident occurs, both with respect to human lives and financial losses. Since fires have previously shown to be responsible for many accidents with severe consequences, the aim of this thesis has been to investigate the risks of fires and/or explosions in the machinery space of oil tankers and container vessels.

By performing a casualty database search and reviewing previous studies in this area, as well as developing a risk model to evaluate the different possible fire scenarios, it is concluded that electrical failures and fuel leaks are responsible for most fire accidents, with generators, pumps and boilers being the most critical components. The expected frequency of a fire and/or explosion accident, calculated for the fleet of interest, amounts to 2.5×10^{-3} incidents per shipyear, resulting in the loss of 0.0003 lives per shipyear. Furthermore financial losses of about 12,000 USD per shipyear can be expected.

Though there are some limitations in the methods used, due to incomplete statistical data and difficulties in drawing general conclusions since every vessel is unique in its design and construction, it is clear that considerable benefits may be obtained by a more detailed cost-benefit analysis for a vessel with respect to fires and explosions.

Written in cooperation with Germanischer Lloyd AG, Hamburg, Germany

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Summary

A considerable part of world merchandise is transported by sea, and with around 150,000 crew members working on the ships of interest, i.e. oil tankers and container vessels, there is a lot at stake in case of an accident, both with respect to human lives and financial losses. Fire on board has been shown to be one of the of the greatest risks on cargo ships, and the aim of this thesis has been to investigate the occurrence and the expected consequences of fires and/or explosions in the machinery space of oil tankers and container vessels.

By collecting statistical casualty data in a database search, as well as performing a literature review the main hazards have been identified, and the expected frequency of fires and/or explosion incidents have been calculated. An internal GL damage database provided considerable incident information along with Lloyd's Register Fairplay's casualty database. To widen the search and get more detailed information the investigation was extended to include previous work on the subject, mainly a report on engine room fires by Nippon Kaiji Kyokai, and an investigation by the US Coast Guard. Next a risk model was developed, which was used to evaluate different incident scenarios, depending on the reliability and effectiveness of the fire safety systems used as well as different outcomes with respect to financial costs and personal fatalities and injuries.

It was shown that generators and leaking fuel pumps were the most critical components and the main fire sources, but that boilers initiated the most explosions. In general electrical failures and fuel leakage were the most common sources of failure. In total a fire and/or explosion frequency of 2.5×10^{-3} ($CI_{90\%}$ $(1.6\text{-}3.9)\times 10^{-3}$) incidents per shipyear can be expected. These accidents are expected to cause the loss of 0.0003 lives ($CI_{90\%}$ 0.00013-0.00061) per shipyear.

Both actual repair costs, the loss in case of a total ship loss (i.e. sinking of a ship or a constructive total loss), and income losses when a ship has to be taken out of service were considered when estimating the financial losses. This resulted in an expected financial loss of about 12,000 USD ($CI_{90\%}$ 4000-25,000 USD) per shipyear due to fires and/or explosions in the machinery space.

There were some difficulties with the method used within the thesis, mainly related to insufficiencies in the level of detail in the incident reports. Furthermore it is noted that almost every vessel is unique with respect to cargo, size, age and design and hence the machinery and the layout of the machinery space varies, making it almost impossible to perform a detailed risk analysis for a generic ship type. Due to these limitations a complete cost-benefit analysis has not been performed, but is instead presented as a qualitative discussion.

Finally, it is concluded that fires and/or explosions in the machinery space pose great threats for loss of lives and that a ship suffering from a fire and/or explosion can be forced to undergo extensive repairs, resulting in major costs. Although difficult to quantify for a generic ship performing a more detailed cost-benefit analysis for a specific vessel is very beneficial.

Sammanfattning

En betydande del av all internationell varutransport sker till sjöss, och med totalt ca 150 000 personer som arbetar på de fartygstyper som berörs inom rapporten, oljetankers och containerfartyg, är det stora värden som står på spel när olyckor inträffar, både vad gäller människoliv och ekonomiska förluster. Brand ombord har visat sig vara en av de största riskerna på lastfartyg, och målet med det här projektet har varit att att utreda förekomsten och de förväntade följderna av bränder och/eller explosioner i maskinutrymmen på oljetankers och containerfartyg.

Genom att samla statistik från olyckor och incidenter i en databassökning samt att genomföra en litteraturstudie har de största riskkällorna kunnat identifieras och den förväntade frekvensen för bränder och/eller explosioner har räknats ut. En intern GL-incidentdatabas har tillsammans med Lloyd's Register Fairplay's olycksdatabas utgjort grunden för informationssökningen. För att utvidga sökningen och få mer detaljerad information har dock även annan litteratur använts, framförallt en rapport om maskinrumsbränder av Nippon Kaiji Kyokai samt en utredning av den amerikanska kustbevakningen. Därefter utvecklades en riskmodell för att utvärdera olika brandscenarier, dels beroende på tillförlitligheten och effektiviteten av olika brandsskyddssystem men också beroende på de efterföljande utfallen för såväl ekonomiska förluster som personskador och dödsfall.

Det konstaterades att generatorer och läckande bränslepumpar är de mest kritiska komponenterna som orsakar flest bränder, medan värmepannor utgör den största risken med avseende på explosioner. Generellt sett var elfel och bränsleläckage de mest förekommande orsakerna. Totalt sett uppgår den förväntade frekvensen för bränder och/eller explosioner i maskinutrymmen till 2,5 $\times 10^{-3}$ ($\mathrm{CI}_{90\%} 1,6 - 3,9 \times 10^{-3}$) incidenter per skeppsår, vilket förväntas orsaka 0,0003 dödsfall ($\mathrm{CI}_{90\%}$ 0,00013-0,00061) per skeppsår.

Både faktiska reparationskostnader, förlusten vid en totalskada (då fartyget förliser alternativt drabbas av en konstruktionsmässig totalskada), och inkomstförluster om ett fartyg måste tas ur drift, inkluderades vid beräkningen av ekonomiska förluster. Detta resulterade i en förväntad kostnad på 12 000 USD ($\mathrm{CI}_{90\%}$ 4 000-25 000 USD) per skeppsår till följd av bränder och/eller explosioner i maskinutrymmen.

Ett par svårigheter konstaterades med valet av metod i rapporten, framförallt med avseende på brister i detaljnivån i incidentrapporteringen. Vidare noterades det att i princip varje fartyg är unikt konstruerat, och att dess egenskaper varierar vad gäller exempevis last, storlek och ålder, vilket har inneburit att det är i praktiken omöjligt att göra en detaljerad riskanalys för en allmän skeppstyp. På grund av dessa begränsningar har ingen fullständig cost-benefit analys genomförts, utan istället förs en kvalitativ diskussion.

Slutligen kan det konstateras att bränder och/eller explosioner utgör stora risker för människoliv och att ett fartyg som drabbas av en brand och/eller explosion kan tvingas genomgå omfattande reparationer, vilket resulterar i stora kostnader. Därför, även om det är svårt att kvantifiera kostnader och förluster för en allmän fartygstyp, kan det medföra stora besparingar att genomföra en mer detaljerad cost-benefit analys för ett specifikt fartyg.

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Finally, this thesis would not have been possible without the help of several people at Germanischer Lloyd who provided us with help and support in understanding the shipping industry.

Katarina Lindgren & Mateusz Sosnowski
Lund, October 2009

Errata

It has been brought to our attention that some of the information in Section 3.2 (Machinery Space Overview) was not entirely correct. We have therefore chosen to make some small adjustments to this section in order to clarify the text.

Katarina Lindgren & Mateusz Sosnowski
Lund, February 2010

Terminology and Definitions

The following sections defines the terms and lists the abbreviations frequently used within the thesis. Notations used in the risk model are described further in Section 4.

Definitions

The following definitions are used throughout this thesis.

AFRAMAX-Tankers
A class of tankers with DWT of 80,000 - 119,999.

Consequence
The outcome of an incident. Described as either financial loss (cost) or personal loss (fatalities/injuries).

Deadweight Tonnage (DWT)
Weight in tonnes of cargo, stores, fuel, passengers and crew on a ship when loaded to its maximum summer loadline.

Detection Time
The time from point of ignition until the first person becomes aware of an incident, either by noticing smoke/heat/other signs of a fire/explosion, or after being brought to attention of an incident by means of an automatic alarm system. Detection is considered early if it occurs within 11 minutes of the ignition.

Explosion
Instantaneous combustion of a combustible gas mixture leading to rapid heat release or pressure rise, or alternatively a mechanical collapse of an enclosed container due to rapid pressure build-up and/or rapidly increasing volume.

Gross Tonnage (GT)
The entire internal cubic capacity of the ship expressed in tons of 100 cubic feet to the ton. Certain spaces are exempted e.g. ballast tanks, bridge or cabins.

Fatality
All deaths occurring in relation to a fire/explosion incident, i.e. either by the fire/explosion itself, during the extinguishing process (e.g. by CO_2 poisoning) or other events following a fire/explosion.

Frequency
The number of incidents occurring per time unit (e.g. per year).

Incident
An unintended event involving fatality, injury, ship loss or damage, other property loss or damage, or environmental damage due to fire or explosion.

Injury
A personal injury is defined as a case where the injury calls for medical attention of the person/-s involved, i.e. where a person requires either acute medical treatment or alternatively where the person seeks medical consultancy later.

Length Overall (LOA)
A ship's length in feet and inches from the extreme forward end of the bow to the extreme aft end of the stern.

Machinery Space
A space or spaces containing propelling machinery, boilers, oil fuel units, generators and major electrical machinery, and includes auxiliary machinery spaces, store rooms, workshops, the shaft alley, and the steering gear room.

Risk
The combination of the frequency and the severity of the consequence.

Risk Control Measure
A means of controlling a single element of risk.

Risk Control Option
A set of risk control measures.

Scenario
A sequence of events from the initiating event to one of the final stages.

Twenty-foot Equivalent Unit (TEU)
An inexact unit of cargo capacity often used to describe container ships and container terminals. It is based on the volume of a 20-foot long inter modal container, but is inexact due to the lack of standardisation on the height of containers.

Abbreviations

All abbreviations used at least once within this report are listed below.

AES	Aerosol Extinguishing System
AFFF	Aquaous Film Forming Foam
$\mathbf{CI}_{90\%}$	90% Confidence Interval, showing 5^{th} and 95^{th} percentiles
CM	Consumer Market
CV	Contingent Valuation
DWT	Deadweight Tonnage
FP	Sub-Committee on Fire Protection (IMO)
FSA	Formal Safety Assessment
FSS Code	International Code for Fire Safety Systems
FTP Code	International Code for Application of Fire Test Procedures
GCAF	Gross Cost of Averting a Fatality
GDP	Gross Domestic Product
GL	Germanischer Lloyd
GT	Gross Tonnage
HFO	Heavy Fuel Oil
HSE	Health and Safety Executive (UK)
IACS	International Association of Classification Societies
IMCO	Inter-Governmental Maritime Consultative Organization
IMO	International Maritime Organization
ISM Code	International Safety Management Code
LTH	Lund Institute of Technology (Sweden)
LO	Lubrication Oil

LOA	Length Overall
LR	Lloyd's Register
LRF	Lloyd's Register Fairplay
MDO	Marine Diesel Oil
MEPC	Marine Environmental Protection Committee
MSC	Maritime Safety Committee (IMO)
NCAF	Net Cost of Averting a Fatality
NFDC	National Fire Data Center (USA)
NFIRS	US National Fire Incident Reporting System
NK	Nippon Kaiji Kyokai
NLR	Naval Research Laboratory (USA)
NTUA	National Technical University of Athens
OREDA	Offshore Reliability Data
POP&C	Pollution Prevention and Control
RPM	Revolutions Per Minute
SAR	Search and Rescue
SDL	Ship Design Laboratory
SINTEF	Selskapet for Industriell og Teknisk Forskning ved Norges Tekniske Hoegskole (Norway)
SIS	Ship Information System (GL)
SOLAS	International Convention for the Safety of Life At Sea
STCW Code	Code for Standards in Training, Certification and Watchkeeping
TEU	Twenty-foot Equivalent Unit
USCG	United States Coast Guard
USFA	United States Fire Administration
VSL	The Value of a Statistical Life
WMU	World Maritime University
WR	Wage-Risk
WTP	Willingness To Pay

Contents

Appendices

List of Figures

List of Tables

1 Introduction

The following sections outline the background and objectives as well as the limitations of this thesis.

1.1 Background

More than 80% of the world merchandise trade by volume is transported by sea, making the shipping industry an important part of world economy and globalisation. Over the past three decades international shipping has increased with an average growth of 3.1% annually, and in 2007 international shipping trade reached 8.02 billion tons. The world fleet keeps expanding at the same rate and amounted to 1.12 billion deadweight tonnage (DWT) in the beginning of 2008. (UNCTAD Secretariat 2008)

Fire on board ships is one of the most serious risks for property and persons, as well as for the surrounding environment (Strandberg 1997). A ship is evidently subject to the same risks of fire as a civil or industrial land structure, but with the difference that help from outside in form of the fire brigade or medical assistance can rarely be relied on. A machinery space contains much machinery and parts necessary for running the ship, and often with the accommodation block located just above.

Reports on the subject, such as a Formal Safety Assessment (FSA) on Crude Oil Tankers submitted to the International Maritime Organisation (IMO) by Denmark (MEPC 2008), show that only 17% of all accidents but as much as 75% of all fatalities from 1980 to 2007 were caused by fires or explosions. The *Critical Review of AFRAMAX* [1] *Incidents Tankers*, (Alissafaki, Aksu, Delautre, Eliopoulou, Mikelis, Papanikolaou & Tuzcu 2006) shows that 83% of all fires started in the aft area (i.e. the machinery space, accommodation block and the bridge). Out of those fires 83% started in the machinery space, which indicates that 2/3 of all fires start in the machinery space.

In 2009 about 4500 container vessels and 7500 oil tankers of interest for this thesis were reported to be in operation (LRF 2009*a*). A rough estimate indicates that about 150,000 persons are working on those ships around the world and as shown above it is clear that fires and explosions in the machinery space are major risks to these workers.

Even though the safety of personnel is a high priority, loss of property and other financial losses could be significant after a fire or explosion, especially if the fire affects the steel structure of the ship or spreads outside the machinery space. An investigation by the US Coast Guard (USCG 1998) shows that 10% of all investigated fires in the machinery space led to a total loss of the ship, where the ship sank in almost half of the cases. With an average load of 2500 Twenty-Foot Equivalent Units (TEU) and in extreme cases up to 14,000 TEU the loss of cargo can be greater than the monetary value of the ship itself.

Given all of the above a more detailed investigation of these types of accidents is called for.

1.2 Objectives

The main issues which will be addressed in this thesis are as follows:

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[1] AFRAMAX is a class of tankers with a deadweight tonnage of 80,000 - 119,999.

> *What are the main risks, and the financial and personal losses of these risks, with respect to fire and explosion in machinery spaces on oil tankers and container vessels? Moreover, how can these risks be reduced or eliminated by practical and reasonable means?*

The purpose of this task is twofold; firstly it is a Master's Thesis at Lund Institute of Technology (LTH) and secondly it is an assignment to perform a risk analysis on the topic for Germanischer Lloyd AG (GL).

1.3 Method

The IMO proposes a process called Formal Safety Assessment for structured risk analysis and identification of risk control options (MSC 2007*a*). By adopting the FSA process the decision makers are able to assess the effect of the proposed regulatory changes in terms of benefits and to relate costs incurred for the industry as a whole or for individual parties affected by the decision. These assessments result in a standardised report for easy comparison.

This thesis follows the basic outline of an FSA but will not result in a formal report as described by MSC (2007*a*). Below follows a description of the method used within this thesis to perform a safety assessment, i.e. (1) *identification of hazards*, (2) *risk analysis* and finally a discussion on (3) *risk control options*. The remaining two steps, (4) *cost-benefit assessment of risk control options* and (5) *recommendations for decision making* are left out (partly due to difficulties in collecting detailed information, although an attempt to show the range of reasonable costs for risk-control options was made). However the model developed is made in such a way that a more detailed analysis (i.e. cost-benefit) can be made on the basis of the findings in this thesis.

There are several different ways to carry out the steps in a risk analysis, depending on the purpose and level of detail of the work. Below follows a short description of how the steps are carried out within this thesis.

Identification of Hazards

In order to determine what the main risks are an identification of the hazards was done initially. Due to our lack of experience in shipping, both with respect to machinery spaces and maritime industry in general, a significant period of time was spent to get familiarised with the field. This was done by interviewing persons within GL and on two field trips on board container ships. Furthermore a literature study was performed to collect information on previous work on the subject, as well as to form a basic understanding of the layout of machinery spaces on oil tankers and container vessels with respect to fire safety.

A case study (referred to as the Thesis Database Search) was performed by use of relevant statistics and casualty data, to investigate common causes, consequences and other information on previous fire and/or explosion incidents on oil tankers and container vessels. The information found in the databases was sometimes not detailed and therefore other sources (i.e. similar reports on the subject) had to be used as a complement to the database search.

Risk Quantitation

After identifying the main hazards a quantitation was carried out on how often the major circumstances causing the incident occur.

In order to quantify the risks a failure frequency was calculated, by comparing the findings in the Thesis Database Search, similar reports and failure rate statistics from a database (OREDA 2002) on offshore component failure data. Due to the nature of the sources the level of detail and the applicability for this thesis varied. Hence the findings were given different reliability and weighted together differently based on the relevance of each source to give the final results.

Consequences

The last step before analysing possible preventative measures, was to calculate the expected loss and/or cost.

Different scenarios and consequences after fires and/or explosions in the machinery space were evaluated by developing an event tree and then estimating the probabilities in each node with the help of the findings in the investigation and discussions with other experts in the field. For the consequences both financial losses and safety costs (i.e. crew injuries and fatalities) were taken into consideration. Although outside the scope of this thesis the model used also provides the possibility to evaluate environmental consequences.

For data processing Microsoft Excel (v 2003) has been used together with Palisade Decision Suite v 4.52, specifically @Risk and PrecisionTree 1.0, to calculate event trees and make Monte Carlo simulations.

Risk Control Options/Cost-Benefit Analysis

By combining the frequency rates found in the risk quantitation step and findings in the consequence analysis it is possible to see where risk reducing measures should be included to be most cost effective. When knowing how much a counter measure reduces the risk it is also possible to see how much the expected loss would be reduced. A comparison of the cost of the measure and the benefit (the expected loss reduction) shows whether the proposed risk control option is cost effective or not.

Due to lack of information this step was carried out as a discussion around two examples to show the range of costs reasonable for improving the safety by these measures.

1.4 Limitations

This thesis is focused on the fire safety in machinery spaces on oil tankers and container vessels during normal operation in port or at sea. Fire risks during ship construction or maintenance in the yard are not considered.

There are a number of different oil tankers and container vessels. As per the assignment from GL the thesis focuses on some specific types of vessels, ships that are considered to be similar in the structure and layout of the machinery space. Specific information regarding these types of oil tankers and container vessels (i.e. Statcodes A33A2CC and A13****) are presented in Section 2.3.1.

Only ships delivered after 1 January 1998, i.e. ships not older then 11 years of age, are taken into consideration in the Thesis Database Search. This boundary condition will affect the number of incidents found in the incident databases and is further discussed in Section 5.1.

The main focus is to calculate the frequency rate of incidents as well as to estimate the expected loss in case of a fire or explosion in machinery space. Therefore a complete cost-benefit analysis was not carried out and instead an attempt was made to estimate the willingness to pay for some counter measures.

Only consequences involving the vessel itself and the crew are included. Therefore incidents such as damages to another vessel after a collision or contact resulting from loss of steering due to the fire or other consecutive damages have not been considered. Liabilities towards third parties, e.g. concerning the cargo of container vessels, and pollution or other environmental impact are also disregarded.

Finally, this report involves only maritime nations that are members of the IMO and have ratified its conventions, and ships built in compliance with the current international regulations.

1.5 Disposition of the Report

Below follows a description of the report structure, with a brief summary of the contents of each chapter.

Chapter 1	The first chapter serves as an introduction and contains background information on the subject of the thesis, as well as objectives and limitations.
Chapter 2	This chapter describes the legal environment, in terms of international maritime regulations and codes, as well as the maritime organisations relevant for this thesis and the internationally recognised Ship Identification Number Scheme.
Chapter 3	Relevant background information, with respect to both the world fleet and a generic machinery space layout, and a description of the required fire safety installations are presented in this chapter.
Chapter 4	This chapter explains the risk model developed for this thesis, both with respect to its structure and contents and the notations used.
Chapter 5	The results of the hazard identification are presented here, along with descriptions of the data sources used.
Chapter 6	All input data in the risk model is discussed in this chapter, including the probability and consequence distributions of technical systems, personal injuries/fatalities and financial losses.
Chapter 7	This chapter summarises the results of the hazard identification and the risk model simulations with respect to expected probabilities and costs. This is followed by a sensitivity analysis.

Chapter 8	A discussion on the possibility of including both personal losses and financial losses in the same analysis is followed by examples of risk control options and a qualitative cost-benefit assessment.
Chapter 9	This chapter contains a discussion on the findings of the database search, literature study and risk model simulations, and ends with the conclusions of the thesis.
Appendix	Statistical data and distribution tables, as well as drawings from a real ship machinery space and detailed results from the risk model simulations are found here. A presentation of the verbal references can also be found in Appendix G.

2 Organisations and Legal Environment

This chapter provides some background information on maritime safety, describing the most important international maritime organisations as well as the legal environment with laws and regulations of interest for this thesis. Furthermore the internationally adopted ship identification and classification system is discussed, and the different ship types included in this report are described in more detail.

2.1 Organisations

The following section briefly describes some of the most important international maritime organisations with respect to safety issues.

2.1.1 The International Maritime Organization

The Inter-Governmental Maritime Consultative Organization (IMCO) was established in 1948 at a United Nations convention after World War II, in response to a growing need of an international regulatory body in the maritime industry. The convention came into force ten years later, in 1958, after being accepted by 21 nations as required. Since 1982 the organisation has been called the International Maritime Organization. (Özçayir 2004)

The main objectives of IMO are summarised in Article 1a of the Convention (IMO Convention 1993), which states that the purpose of the organisation is as follows:

> *To provide machinery for co-operation among Governments in the field of governmental regulation and practises relating to technical matters of all kinds affecting shipping engaged in international trade, and to encourage the general adoption of the highest practicable standards in matters concerning maritime safety, efficiency of navigation and prevention and control of marine pollution from ships; and to deal with administrative and legal matters related to the purposes set out in this Article.*

During the first decades of its existence the main objectives of the organisation was to form regulations in order to standardise the safety requirements and quality within the world wide shipping industry. Later focus shifted and IMO gradually adopted a more proactive approach to maritime safety. This has been achieved for example by working actively to implement the conventions, with the hope of giving all maritime nations, including developing countries, the necessary financial and technical tools to undertake the required actions. As part of the technical assistance programme the World Maritime University (WMU) was founded in Malmö, Sweden in 1983. (Mitroussi 2004)

At present IMO has 168 member states and 3 associate members (IMO 2009*c*), resulting in all major maritime nations and most of the world fleet being involved in its work. The organisational structure of IMO is centred around its Assembly and Council as well as five Committees and a Secretariat. All members are represented in the Assembly, which meets every two years and constitutes the organisation's highest governing body. IMO's everyday work is supervised by its Council, an executive organ which is elected by the Assembly and consists of 40 member states. Furthermore, the technical work is carried out by the Committees: the Maritime Safety Committee (MSC), Legal Committee, Maritime Environment and Protection Committee (MEPC), Technical Co-Operation Committee and Facilitation Committee. (IMO 2009*d*)

2.1.2 Germanischer Lloyd

With about 6800 ships in its fleet, responding to about 80 million Grosse Tonnage (GT), GL is one of the largest ship classification societies in the world. Of the world's approximately 50 classification societies, 10 are members of the International Association of Classification Societies (IACS), and together class about 94% of the commercial tonnage involved in international trade (IACS 2009). GL was founded in Hamburg, Germany in 1867 and also serves as an international inspection, certification and technical consultancy company. (GL 2009*b*)

The main role of a classification society is to establish technical standards that fulfil the IMO regulations, and to perform inspections during the design and construction stages as well as during ship operation to check whether the regulations are complied with. After completing construction of a vessel the ship builder applies for a certificate, attesting that the vessel complies with a certain set of standards. In order to maintain its class the vessel regularly has to undergo surveys to ensure that the safety level is satisfactory. Should the ship fail to meet the requirements the class can be suspended or withdrawn. (IACS 2009)

More details on the GL fleet and the world fleet are found in Section 3.1. Since incident data used within this thesis mostly originate from GL classified ships, other classification societies are not described in further detail within this report.

2.1.3 Lloyd's Register Fairplay

Lloyd's Register traces its origins to the late 17th century. The Register Society was formed with the first Register of Ships being published in 1764. In 2001 a new joint venture company called Lloyd's Register Fairplay (LRF) was formed. LRF is one of the biggest providers of maritime information and is also the originating source for the IMO Ship Number, IMO Company Number and IMO Registered Owner Number. Furthermore it is the only organisation with authority to assign and validate these numbers (see Section 2.3 for further details). (LRF 2009*e*)

2.2 Legal Environment

The following section describes the most important regulations with respect to maritime safety.

2.2.1 International Convention For the Safety of Life At Sea

The first conference on *Safety of Life At Sea* (SOLAS) was held in 1913, in response to the sinking of the *Titanic* one year earlier, where about 1500 people lost their lives. In 1914 the first version of SOLAS was ratified, and further conventions were adopted in 1929, 1948, 1960 as well as in 1974, the SOLAS convention which is still in force today. Early on the regulations were mostly introduced in direct response to major accidents. After the Titanic disaster the safety of passenger ships was for example brought to attention, resulting in the first SOLAS convention focusing on adequate life saving equipment. Furthermore, as a result of several ship fires in the 1920's, numerous fire protection regulations were introduced in the 1929 SOLAS version. (Kuo 2007)

At present 158 nations have ratified the SOLAS 1974 Convention (IMO 2009*c*). The convention specifies minimum safety requirements with respect to ship construction, equipment and operation, with fire protection requirements stated in Chapter II-2. When ratifying the convention the *contracting government* undertake the responsibility to implement the regulations within the ships under its flag. (SOLAS 2009)

The SOLAS convention in force today, though adopted 35 years ago, has been updated and amended several times over the last few decades to maintain a satisfactory safety standard. Below follows a description of the amendments relevant for the ship types of interest for this thesis, with the years listed below stating the date when the amendments entered into force. The regulations were however, in most cases, adopted by the IMO a couple of years earlier. The following information is collected from the IMO website IMO (2009*a*).

1984 The fire protection chapter was re-arranged to incorporate the requirements of resolution A.327(IX) recommendation concerning fire safety requirements for cargo ships, including 21 regulations involving separation of accommodation spaces from the remainder of the ship by thermal and structural boundaries, protection of means of escape, early detection, containment or extinction of any fire and restricted use of combustible materials. Other amendments related to provisions for halogenated hydrocarbon extinguishing systems.

1986 Improvements to the 1984 amendments.

1992 Amendments included regulations concerning fixed gas fire-extinguishing systems, smoke detection systems, arrangements for fuel and other oils and the location and separation of spaces.

1996 Improvements for regulation 15, with respect to fire protection arrangements for fuel oil, lubrication oil and other flammable oils.

1998 Extensive modifications including the general introduction, Part C (fire safety measures for cargo ships) and Part D (fire safety measures for tankers). The changes made mandatory a new International Code for Application of Fire Test Procedures (FTP Code) intended to be used by administrations when approving products for installation in ships flying their flag.

2002 Revised fire protection chapter of SOLAS (construction, fire protection, fire detection and fire extinction) incorporating substantial changes introduced following a number of serious fire casualties. The revised chapter includes seven parts, each including requirements applicable to all or specified ship types. A new International Code for Fire Safety Systems (FSS Code) was introduced as well, and made mandatory under the new chapter, which includes detailed specifications for fire safety systems.

2010 Amendments relating to Regulation 9 - Containment of fire, to include a requirement for water-mist nozzles which should be tested and approved in accordance with the guidelines approved by IMO, and in Regulation 15 - Arrangements for oil fuel, lubricating oil and other flammable oils, and new text relating to the application of the regulation to ships constructed on or after 1 February 1992 and on or after 1 July 1998.

2.2.2 Other Laws Of Interest

The following regulations apply to maritime safety. They are partly relevant for this thesis but do not directly affect the analysis, and are therefore only briefly described.

Standards in Training, Certification and Watchkeeping Convention and Code - The STCW Code applies to all ships visiting ports in states that have ratified the convention and mainly focuses on the qualifications on the crew on board (STCW Convention 2001).

International Code for Fire Safety Systems - The FSS Code is mandatory according to the SOLAS regulations and states international engineering specifications for the required fire safety systems, including design, installation and maintenance requirements (FSS Code 2007).

International Code for Application of Fire Test Procedures - The FTP Code has been mandatory since 1998 and contains international requirements for laboratory testing, type approval and fire test procedures for various surface and covering materials, thermal boundaries etc. (FTP Code 1998).

International Safety Management Code - In order to achieve the safety objectives the ISM code requires the shipping company to establish a Safety Management System. Furthermore the company is required to develop and document a policy outlining how the objectives are to be achieved. (IMO 2009*b*)

2.3 IMO Ship Identification Number Scheme

In order to keep track of all vessels in international operation Lloyd's Register (LR) has kept a database where every ship is assigned a unique seven digit identification number. Unlike the ship name, which most probably changes during the lifetime of a ship, the identification number remains the same. The IMO ship identification number scheme was adopted in 1987 in accordance with the IMO Resolution A.600(15) (IMO 1987). The scheme used the then existing ship register numbering system from LR. LRF is now the only organisation with the authority to assign and validate these numbers on behalf of the IMO. (LRF 2009*c*)

The scheme assigns IMO ship numbers to propelled, sea-going merchant ships of 100 GT and above though there are exceptions, e.g. vessels solely engaged in fishing or ships engaged on special services (such as lightships or search and rescue (SAR) vessels). (IMO 1987) LRF has extended the scheme on a voluntary basis to include some of the ships that are not required to be assigned an IMO ship number. The IMO ship number is never reassigned to another vessel which means that the database holding all IMO ship numbers also serves as a historical database.

LRF is also responsible for maintaining the *IMO unique company and registered owner identification number scheme* which works in the same way as the ship identification number but identifies each company and registered owner managing ships of 100 GT and above engaged on international voyages. To keep every identification number unique some rules exist about how these numbers are transferred in the event a company and/or registered owner sells, or otherwise disposes of a ship. Just like the IMO ship identification number the company number is never reused. (LRF 2009*c*)

2.3.1 Statcode

There are many different vessel type data coding systems in use today. None of the currently maintained systems completely meets the requirements for performing an aggregated analysis on detailed vessel type descriptions for a particular vessel. A popular coding system that meets some of the requirements is the Statcode, which is provided and maintained by LRF. One problem with the Statcode was previously that it did not provide enough detail. A decision was therefore made to extend the coding system to a fifth level that contains more specific vessel information.

The coding system assigns each vessel a specific alphabetic and digit combination where every level gives a certain piece of information about the ship. At level 1 for example the ships are roughly divided into: A - Cargo-carrying vessels, B - Working-vessels and some others categories. Level 5 gives information about the hull shape and the type of cargo it carries (LRF 2009*c*). In total there are 327 different ship types in the Statcode 5 coding system (LRF 2009*d*). The Statcodes and descriptions of the ship types relevant for this thesis are shown in Table 2.1.

*Table 2.1: All Statcodes of interest for fire and explosion within this thesis (LRF 2009*d*).*

Statcode	Definition	Description
A33A2CC	Container Ship (Fully Cellular)	A single deck cargo vessel with boxed holds fitted with fixed cellular guides for the carriage of containers.
A13****		
A13A2TS	Shuttle Tanker	A tanker for the bulk carriage of crude oil specifically for operation between offshore terminals and refineries. Is typically fitted with bow loading facilities.
A13A2TV	Crude Oil Tanker	A tanker for the bulk carriage of crude oil.
A13A2TW	Crude/Oil Products Tanker	A tanker for the bulk carriage of crude oil but also for carriage of refined oil products.
A13B2TP	Products Tanker	A tanker for the bulk carriage of refined petroleum products, either clean or dirty.
A13B2TU	Tanker (unspecified)	A tanker whose cargo is unspecified.
A13C2LA	Asphalt/Bitumen Tanker	A tanker for the bulk carriage of asphalt/bitumen at temperatures between 150 and 200°C .
A13E2LD	Coal/Oil Mixture Tanker	A tanker for the bulk carriage of a cargo of coal and oil mixed as a liquid and maintained at high temperatures.

3 Generic Description of Fleets and Ships

This chapter outlines and explains the fundamentals of a generic ship machinery space and its components. Furthermore a comparison is made between the present world fleet and the GL classed fleet of oil tankers and container vessels.

As part of the thesis work two study visits were carried out to gain a general understanding of the typical ship machinery space and the routines on board, and also to interview the crew on their thoughts on fire safety. The following two container ships were visited:

Container Vessel I The first ship was visited in June 2009 for a voyage on the Kiel Channel. The ship is a container vessel, run by a 4-stroke diesel engine, was built in 2004 and is a typical feeder of about 800 TEU.

Container Vessel II This container ship was built in 1994 and has a TEU of about 1,500. It was visited while in harbour in July 2009. The vessel has a 2-stroke diesel engine and though being constructed prior to 1998 the ship is more representative of the world fleet with respect to size and machinery layout than *Container Vessel I* and has therefore been used throughout this report (referred to as *M/S Thesis*) to illustrate a typical ship and a generic machinery space.

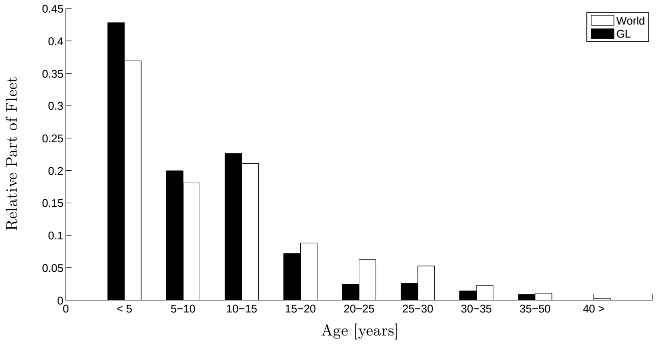
3.1 Oil Tanker and Container Fleets

The collected incidents are mostly taken from GL's Damage Database (GL 2009*a*) (see Chapter 5.1) so therefore it is of interest to see whether the GL classed fleet of tanker and container vessels is representative of the world fleet.

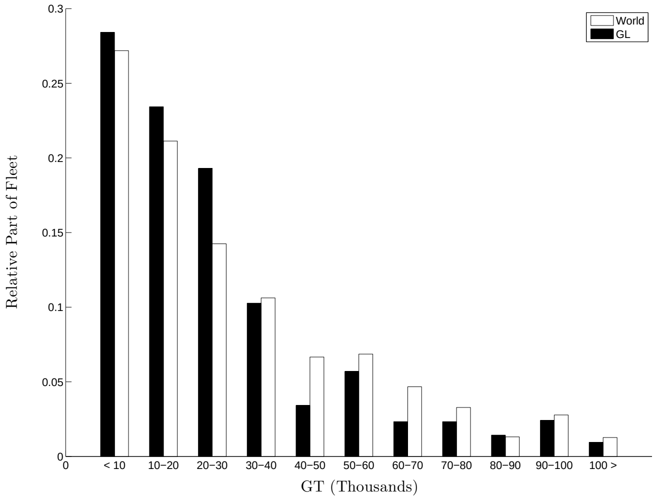
In total 43.8% of all container vessels and 1.5% of all tanker vessels of interest are GL classed (LRF 2009*b*). Two significant characteristics of a ship concerning the layout and condition of machinery space are the GT and age of the ship. The GT measures the cubic capacity of the ship, and ships of similar size tend to have similar engine power and similar machinery space layout. The age shows to which edition of SOLAS the ship was built and is also believed to indicate the degree of wear on the machinery. Below follows a comparison between the world fleet and the GL fleet and, although not identical, the GL fleet is considered to be representative of the world fleet for this thesis. This is discussed further in Sections 3.1.1 and 3.1.2. More detailed statistical data are found in Appendix A.

In the remainder of the thesis the two categories of ships (i.e. oil tankers and container vessels) are joined together since they are similar regarding machinery spaces and layout, and due to limitations in the available data it has been considered more relevant to perform one analysis rather than to make separate analyses.

A ship's age will largely affect the standard and condition of the machinery space. Depending on the year of construction, a ship complies with the regulations of that time although some changes in the safety regulations are mandatory for all ships and rearrangements to adopt to new regulations have to take place. By calculating the age of all ships that have been lost or scrapped up until today an average life time of 25 years for oil tankers and container vessels is expected (LRF 2009*b*).



(a) Distribution of age.



(b) Distribution of GT.

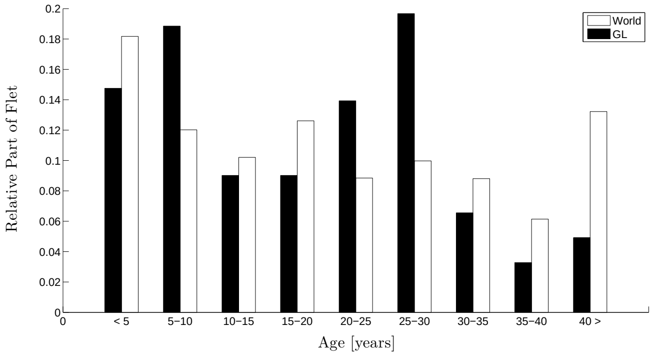
Figure 3.1: Comparison between the world fleet and GL fleet of container vessels.

3.1.1 Container Fleet

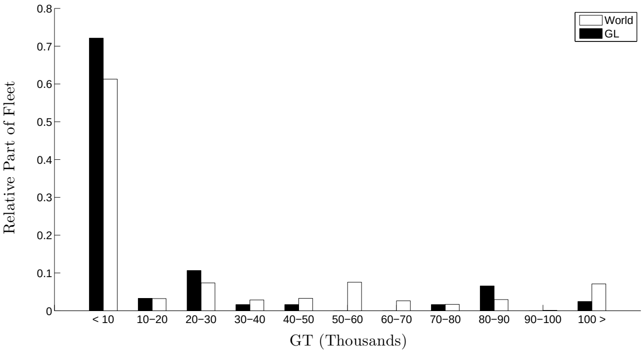
GL has the single largest fleet of container vessels (Statcode A33A2CC) of all classification societies. With approximately 2100 out of 4800 ships a share of slightly more than 40% of the world fleet would suggest that the GL fleet is fairly representative regarding GT and age. This is also confirmed in Figure 3.1.

3.1.2 Tanker Fleet

The GL fleet of tankers is much smaller in relation to the container fleet; 1.5% of the world fleet of the tankers of interest are GL classed. This might suggest that the GL fleet would not be as representative as the container fleet. As illustrated in Figure 3.2 the difference is slightly larger than for container vessels but the general trends are alike. Appendix A



(a) Distribution of age.



(b) Distribution of GT.

Figure 3.2: Comparison between the world fleet and GL fleet of oil tanker vessels.

shows a more complete list of data over the fleets and by comparing the average and mean values the difference is fairly small. For age the average values (World/GL) are (21.5/18.8) and median (18.3/18.8) years, and for the GT the same variables show (26,684/16,319) and (3236/2282). Therefore, although the GL fleet is such a small percentage of the total world fleet, it is considered a good representative. Furthermore it is more important that the larger fleet of container vessels is representative than the small number of 122 oil tankers. This small difference does not significantly affect the result. Therefore, in this thesis, the GL fleet of oil tankers is considered to be representative for the entire world fleet. Even though the number of oil tankers is relatively small compared to the container ship fleet, oil tankers and container vessels are fairly similar and therefore all data have been included in the analysis.

3.2 Machinery Space Overview

The general arrangement of the machinery space is quite similar in container vessels and oil tankers. A highly simplified schematic flowchart for fuel and auxiliary systems as well as the main components is shown in Figure 3.3. More detailed drawings, showing the machinery space layout of the generic ship *M/S Thesis* are presented in Figures B.1 and B.2.

3.2.1 Propulsion

Most container ships and oil tankers are run by a single fixed pitch propeller, which in turn is connected to the main engine via an intermediate shaft. The main engine runs on heavy fuel oil (HFO) or marine diesel oil (MDO) and is started by high pressure compressed air, being released synchronised into the cylinders, causing mechanical movement of the engine, and starting of the combustion in the first cylinder which completes a compression stroke.

Depending on the quality of the fuel (HFO or MDO) it has to be treated in several steps before entering the engine to remove dirt particles and water. After passing through the engine any excess fuel is pumped back to the fuel tank for re-use. (van Dokkum 2003)

3.2.2 Power Supply

Three diesel generators are usually relied on for the ship's power supply during normal operation. Depending on the arrangement of the machinery space a shaft generator might be in place, using the power of the rotating propeller shaft to generate electricity. Furthermore, a steam turbine is a third potential power source, run by the heat of the exhaust gases of the main engine. In order to secure the power supply for essential users such as steering gear and navigation equipment an emergency generator is required and must be located separate from the main machinery space. The main switchboard serves as a connection between the generators and the power consumers under normal ship operation. A separate emergency switchboard is also provided to give power to prioritised functions such as navigation and propulsion. (van Dokkum 2003)

3.2.3 Auxiliary Systems

Various auxiliary systems are in place in a ship machinery space to support the machinery and its functions. These include systems for cooling, heating, lubrication, fresh water, bilge pumps and ballast. Since these systems are of minor importance for this thesis they are not described in further detail.

3.2.4 Main Components

The following section describes the various machinery space components and their function. The numbers in brackets refer to the locations as shown in Figure 3.3. An example of the location of the same components can be found in Figure B.1 and B.2. Further information about the systems or components can be found in literature such as Taylor (1990) or van Dokkum (2003).

Auxiliary Engines (9) Diesel driven generators for the ship's power supply during normal operation in port and at sea, if no shaft generator is active. To secure the power supply for essential components such as steering gear and navigation equipment an emergency generator is always required and is located in a separate compartment from the main machinery space.

Boiler (10) While generating steam from water or heating thermal oil, the auxiliary boiler is heated with fuel, and the exhaust gas boiler is heated with diesel engine exhaust gas.

The heat is basically needed for Heavy Fuel Oil tank heating, fuel heaters (6) in the engine room and general ship's heating. In case of steam, see also Turbine (14)

Blower (1) There are two kinds of blowers in the engine room: *engine room blowers/ ventilators* and *auxiliary blowers of main engine*. The *engine room blowers* are moving air into the engine room, wherefrom the diesel engines and compressors are commonly taking the air, whereas the *auxiliary blowers* are integral parts of a 2-stroke main engine, with the only purpose of supplying air when starting the engine, since the turbochargers are still not rotating and unable to supply air in this condition.

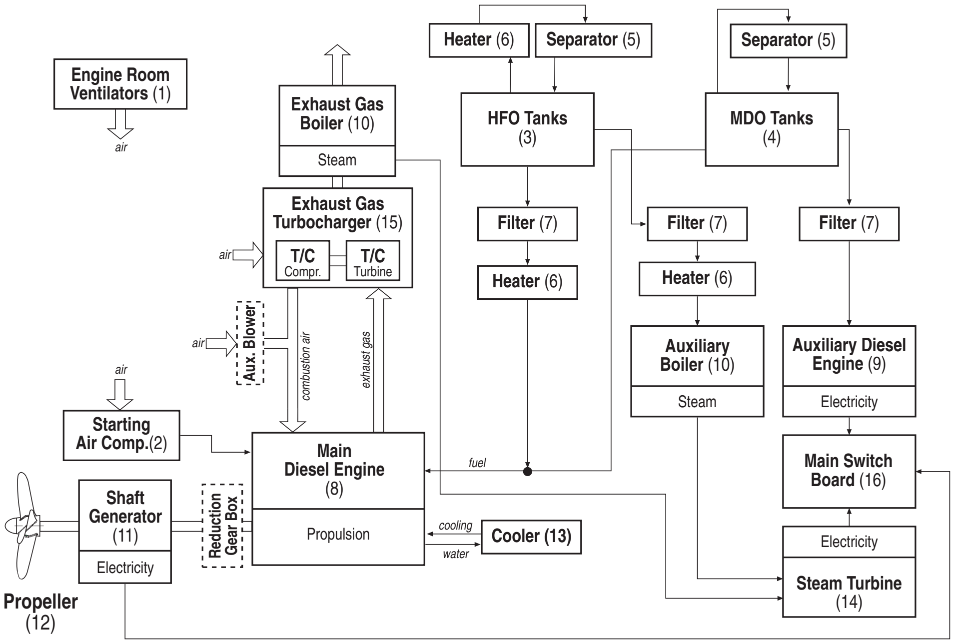


Figure 3.3: Schematic overview of machinery systems and components, which are described in Section 3.2.4. Figure created in consultation with Illge (2010).

Filter (7) Various filters are in place throughout fuel system to separate dirt particles from fuel and lubricating oils.

Fuel Two different types of fuel are generally used for the main engine: **marine diesel oil (4)** or **heavy fuel oil (3).** Heavy fuel is the cheapest but requires cleaning and heating prior to use and produces dirty exhaust gases whereas diesel oil is more expensive but cleaner and more manageable. On board the ship the fuel is stored in bunker tanks from where it is pumped into smaller day tanks in the machinery space.

Heater (6) Due to the high viscosity of the heavy fuel oil it must be heated before entering the engine in order to be used properly.

Heat Exchanger (13) The motor block of each diesel engine needs cooling to prevent overheating from inner combustion. The heat exchangers are arranged for internal heating purposes and for heat disposal by sea water circulation overboard.

Lubrication Lubrication oil flows constantly through each engine or motor to reduce friction and wear. Various pumps and filters are in place throughout to ensure smooth running of the system.

Main Engine (8) The main engine on an oil tanker or container vessel is usually one of the following types: a medium-speed four stroke diesel engine or a low-speed two-stroke diesel engine. A two-stroke engine of the same cylinder volume and RPM develops almost twice the power of a four-stroke engine. It can operate with propeller speed, which keeps the transmission simple, but needs a separate auxiliary blower for combustion air supply during start. An equivalent or better power to mass ratio for four-stroke engines can be achieved, if the same is running 4-5 times propeller speed. This solution needs a reduction **gearbox** .

Pumps Different pumps are provided for different media and purposes. The important permanent running pumps are arranged in pairs, whereof one is active and one in stand by. The pumps for occasional service are arranged as single installations. Those pipe systems are designed to arrange backup by other pumps, serving the same media.

Propeller (12) A container ship's or oil tanker's propulsion is in most cases realised as a combination of a reversible two-stroke main engine and a fixed pitch propeller, or as a combination of a non reversible four-stroke engine together with reduction gear and controllable pitch propeller.

Purifier/Separator (5) Before use the heavy fuel oil must be cleaned, which is done in steps before the fuel enters the engine. From the main tank it is pumped to a settling tank where water and dirt sinks down before the oil is pumped through separators and into the day tank. The dirt is pumped into the sludge tank and later taken care of ashore or disposed of by an incinerator.

Shaft Generator (11) A propeller shaft driven generator, to generate electric energy at sea from the operating main engine, to save operation of auxiliary engines.

Starting Air Compressor (2) The main engine is started by high pressure compressed air, being released synchronised into the cylinders, causing mechanical movement of the engine, and starting of the combustion in the first cylinder which completes a compression stroke.

Steam Turbine (14) If the vessel's steam producing capacity is used to full extent, and the exhaust gas boilers behind the diesel engines are maximised, steam generation may be sufficient to run a steam turbine for electric power generation at sea.

Switchboard The **main switchboard (16)** serves as a connection between the generators and the power consumers as well as a protection against overload and short-circuits in the installations. A separate **emergency switchboard** is provided for the emergency generator.

3.3 Fire Safety Systems

The following sections describe the fire safety systems required according to the SOLAS (2009) regulations in general for oil tankers and container vessels. There are however exceptions and further requirements may apply for certain ships or specific cargoes.

3.3.1 Structural Fire Protection

The general requirements state that all vessels must be subdivided by thermal and structural boundaries to prevent spread of fire from the space of origin. Furthermore all openings and penetrations must achieve equivalent requirements. The machinery space must generally be separated from other spaces by bulkheads and decks achieving *Class A 60 minute ratings*; hence separations must be constructed of steel or equivalent materials and be insulated with non-combustible materials to ensure heat insulation and containment of smoke and flames for the required test period (60 minutes). (SOLAS 2009)

3.3.2 Fire Detection and Alarm Systems

Generally on ships fixed automatic fire detection and alarm systems as well as manually operated call points are required to be installed. The fire detection system should be operated by either heat, smoke, flames, other combustion products, or a combination or the above. Installation requirements and further details on spacing and functional requirements of the detection and alarm systems are specified in the FSS Code (2007).

Furthermore, all periodically unattended machinery spaces are required to be provided with a fixed automatic fire detection and fire alarm system. The general regulations require the detection system to *detect rapidly the onset of fire* throughout the entire machinery space, under any normal operating conditions with respect to ventilation and temperature. Normally use of only heat detection is not permitted, though there are exceptions for areas with restricted height or areas especially suited for heat detection.

An automatic fire alarm system is required to be connected to the detection system, in a way that both visual and audible signals are installed to notify the navigating bridge and the engineer officer on duty. (SOLAS 2009)

3.3.3 Portable Fire Extinguishing Equipment

All machinery spaces are required to be equipped with portable fire extinguishers as follows (SOLAS 2009):

Machinery Spaces Containing Oil-Fired Boilers Or Oil Fuel Units

- One foam applicator unit in each boiler room or at an entrance outside of the boiler room.
- Two foam extinguishers or equivalent in each boiler room and in each space where a part of the oil fuel installation is situated.
- Not less than one foam-type extinguisher of at least 135 l capacity in each boiler room.
- 0.1 m^3 sand or other approved dry material. This may be substituted for a portable extinguisher.

Machinery Spaces Containing Internal Combustion Machinery

- One portable applicator unit.

- In each space foam-type extinguishers of at least 45 l capacity or equivalent, sufficient in number to enable foam or its equivalent to be directed on to any part of the fuel and lubricating oil pressure systems, gearing and other fire hazards.
- Sufficient number of portable foam extinguishers or equivalent which should be located so that no point in the space is more than 10 m walking distance from an extinguisher and that there are at least two such extinguishers in each space.

Since portable fire fighting equipment is always required to be provided within the machinery space it is assumed that the crew will generally attempt a manual fire fighting effort as a first counter measure in case of a fire. A discussion on the probability of success of such an extinguishing effort is found in Section 6.1.4.

3.3.4 Sprinkler System

Machinery spaces above 500 m^3 in volume on cargo ships of 2000 GT and above are required to have a *fixed local application fire-fighting system*. The fixed water-based or equivalent fire-fighting system should have both automatic and manual release capabilities and must cover the following areas (SOLAS 2009):

- The fire hazard portions of internal combustion machinery used for the ship's main propulsion and power generation.
- Boiler fronts.
- The fire hazard portions of incinerators.
- Purifiers for heated fuel oil.

The above sprinkler system requirements apply to all ships constructed on or after 1 July 2002. Since the main focus of the thesis is to investigate the risk situation within ships in the present world fleet and in the future it is assumed that the fixed local sprinkler system requirements apply to all ships of interest. The reliability of such a sprinkler system in the machinery space fires is discussed further in Section 6.1.5.

3.3.5 Fixed Fire Extinguishing System (CO_2)

The machinery space of a vessel is required to be provided with one of the following types of fixed fire extinguishing systems (SOLAS 2009):

- A fixed gas fire-extinguishing system,
- A fixed high-expansion foam fire extinguishing system, or
- A fixed pressure water-spraying fire extinguishing system.

As per the regulations, fire extinguishing systems using Halon 1211, 1301, 2402 or perfluorcarbons are prohibited. Regardless of the type all fire extinguishing systems must comply with the requirements specified in the *FSS Code*, with respect to design, installation and maintenance of the system. (SOLAS 2009)

Busche (2009) estimates that 99% of all oil tankers and container vessels in the current world fleet are provided with CO_2 systems. Therefore this system will be the main focus within this thesis. Other systems such as full coverage sprinkler systems or high-expansion foam systems will not be described in further detail.

A gaseous fire extinguishing media such as CO_2 affects its environment thermally, by cooling the surrounding gas. Since it only affects the fuel in the gas phase and does not cool the fuel itself the extinguishing concentration of the CO_2 must be constantly maintained throughout the space until the fire is completely extinguished. Otherwise, if the CO_2 concentration is lowered due to ventilation, the fire may re-ignite again. (Särdqvist 2002)

Before releasing the CO_2 some safety measures must be taken by the crew. Firstly all crew members must be accounted for to make sure that no one is left in the space. Since CO_2 is both toxic and reduces the oxygen levels in the air it is highly dangerous even at short exposure times (Särdqvist 2002). Secondly all ventilation flaps must be manually closed to maintain an extinguishing concentration of the gas within the machinery space. Under normal circumstances these safety procedures result in a delay of approximately 20 minutes before the CO_2 is released (Ionel 2009, Zalevski 2009). The effectiveness and reliability of CO_2 systems is discussed further in Section 6.1.6.

3.3.6 Fire Fighting Equipment

All ships are required to be provided with fire pumps, mains, hydrants and hoses as well as personal safety equipment such as fire fighter's outfits and breathing apparatus to enable fire fighting efforts by the crew. Below follows a brief description of the required equipment. A discussion on the effectiveness of a fire fighting effort can be found in Section 6.1.7.

Periodically unattended machinery spaces of cargo ships should be provided with immediate water delivery from the fire main system at suitable pressure. On ships of a 1000 GT and above at least two independently driven fire pumps are required, with the emergency fire pump located in a separate space. (SOLAS 2009)

With respect to personal equipment at least two fire fighter's outfits are required on a ship. On tankers another two outfits must be provided. (SOLAS 2009) All outfits must, apart from clothing and helmet, include self-contained compressed air-operated breathing apparatus and a fire proof lifeline (FSS Code 2007).

4 Risk Model

Depending on the purpose and the background information available there are several different ways of performing a risk analysis. In general qualitative approaches are easier to apply (smaller effort and not so resource demanding) but provide the least degree of insight. On the other hand quantitative approaches are most demanding on resources and skills but can potentially deliver much detail and understanding if significant data is provided.

The aim of this thesis was to develop a quantitative risk model for fire and/or explosion incidents in the machinery space. As mentioned above the available information influence the refinement of the risk model. The evaluation of the incident reports show that the available reports provide only limited insight views. This is considered in the development of the risk model, and a more qualitative approach is used especially for the cost-benefit analysis.

The method used in this thesis is often referred to as a bow tie analysis. See Figure 4.1. The idea is quite simple; to have an event, in this case fire or explosion in machinery space in the middle, and on the left hand side make a fault tree to find out the threats whereas on the right hand side have an event tree to show the consequences.

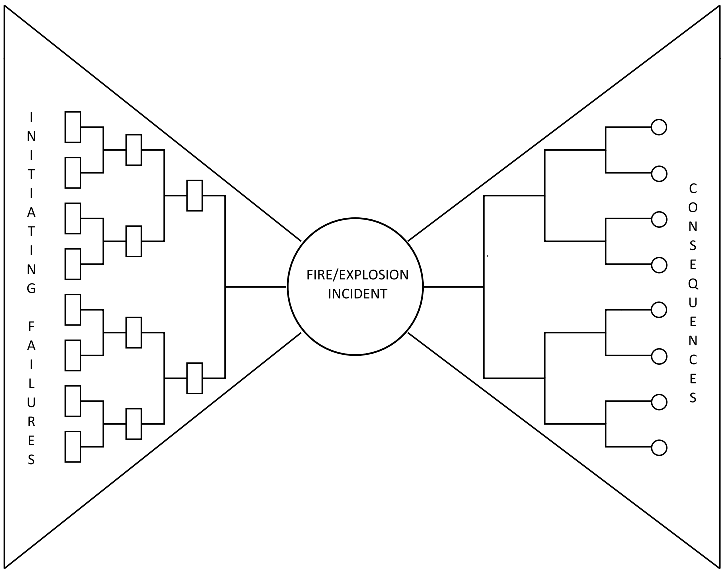


Figure 4.1: Schematic overview of a bow tie analysis approach

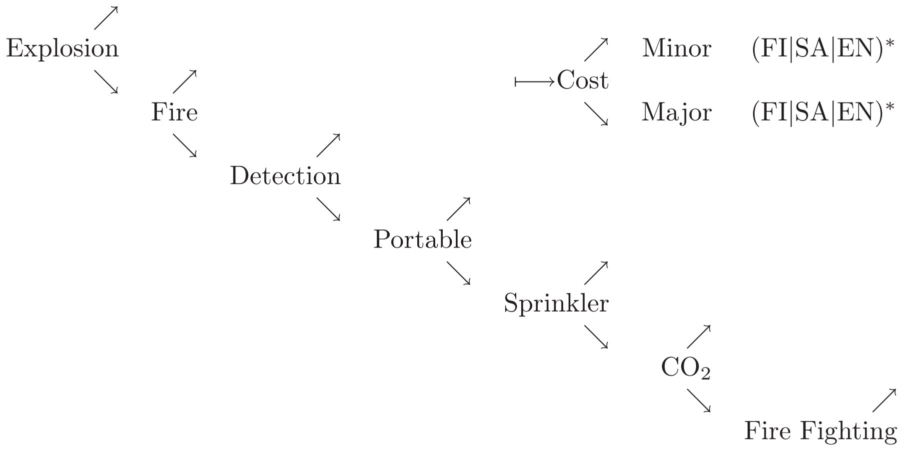
4.1 Hazards/Frequency Rate

The hazard identification has been carried out by combining different statistical and historical sources. In order to identify the hazards different incident reports from fires in machinery spaces were studied, together with interviews with people from the maritime industry. As described in Chapter 3 two study visits were made on two different container vessels. These visits provided a lot of information and understanding on the greatest risks and the layout of machinery spaces. Due to the scarcity of information provided by the incident reports other sources were consulted, such as the NK (1994) report and the USCG (1998) investigation. A more detailed description of this follows in Section 5.

Once the hazards were identified an analysis was made to calculate the incident frequency rate per shipyear. This was also done with the help of database searches and historical information, and in order to get more information a database over failure rates for offshore components (OREDA 2002) was used.

4.2 Consequences

The model used to calculate the consequences is based on an event tree. An event tree offers a simple overview of various events and outcomes of these. Most of the branches are means of suppression with the possibility of successful (yes) or not successful (no) fire extinguishing. When a fire is put out by the given system on one branch it goes straight to costs where it is split into a major or a minor cost. These costs are divided into financial costs and personal losses in order to analyse them separately (Although not used within this thesis an option to analyse environmental costs is also provided). If the fire is not put out it goes to the next means of suppression. The different options are given in Table 4.1. The model follows the path in Figure 4.2 and two schematic figures on the actual tree structure can be found in Figure C.1 and C.2 (depending on whether or not the event is initiated by an explosion).



* FI=Financial, SA=Safety, EN= Environmental

Figure 4.2: Schematic figure over the model for the progression of a fire/explosion.

One overall assumption in the model is that the means of extinguishing will take place in a given order, i.e. /Portable/Sprinkler/CO_2/Fire Fighting/. This is not always true but is considered the most likely order of trying to put out a fire, based on the standard proceedings in case of an emergency (Ionel 2009, Zalevski 2009). Specific assumptions on each branch are discussed further in Chapter 6.

In all binary nodes the probability of the *yes* branch (1) is estimated (for costs this is the *minor* branch) and for Detection the *none detection* probability is estimated. Since the numbers (except costs) are probabilities, the branch in each node that has not been estimated is defined automatically as 1-P(estimated). To take the uncertainties identified in

Table 4.1: Branches and identification system used in the event tree.

	Name	0	1	2
	Explosion	No	Yes	-
	Fire	No	Yes	-
	Detection	None	Early	Late
Means of extinguishing a fire successful or not	Portable	No	Yes	-
	Sprinkler	No	Yes	-
	CO_2	No	Yes	-
	Fire Fighting	No	Yes	-
Financial and safety	Cost	-	Minor	Major

the investigation of the casualty reports into account the risk model was developed in a way that allows for defining distributions for all probabilities and costs used in the model. In the model a distribution is set once and can then be linked to several places where the outcome should be the same.

Table E.3 shows the distributions used in each node. Although environmental costs are not considered in this thesis the model gives the possibility to add costs for this as well.

4.3 Notations

The event tree is built from the initiating event *fire or explosion in the machinery space.* The following items represent the main branches of the tree;

/Explosion/Fire/Detection/Portable/Sprinkler/CO_2/Fire Fighting/Cost/

The possible outcomes of every event are stated in Table 4.1. If there is no fire (i.e. only explosion) or if the fire is extinguished by any of the given means the scenario proceeds directly to its consequence branch. The numbers 0-2 enables identification of the branch/-es.

As an example /1/1/1/0/0/1/-/2/ means: Explosion-Yes, Fire-Yes, Detection-Early, Portable-Not successful, Sprinkler-Not successful, CO_2 system-Successful, Cost-Major. There is also a possibility of addressing several branches in one sequence e.g. /1,2/1/1,2/0/0/1/-/2/ which includes major costs for all fires, not only following an explosion and that are extinguished by the CO_2 system, regardless of the detection time.

Below follows a short description of the used distributions and how they are designated in this thesis. A more complete description of the specific type of distributions can be found in Vose (2000).

- Triangular distributions give the possibility to set a minimum and maximum value together with a most probable which results in a rather heavily simplified estimation at the edges. Triangular distributions are described as T(A, B, C), (A=minimum, B=most probable, C=maximum value).
- Uniform distributions are only defined by a minimum and maximum value with the same probability for every value. Uniform distributions are described as U(A, C).
- For probability distributions for different means of fire suppression (i.e. not costs) the minimum and maximum values (i.e. A and C) are set as a percentage of the most

probable value (i.e. B). This is described as the uncertainty interval and the percentages are given as D/E (D=lower limit, E=upper limit).

- Beta distributions offer a fairly simple way of modelling a parameter with the possibility to set minimum and maximum values. The two values α_1 and α_2 determine the most probable value and also the probability slope towards the minimum and maximum values. Beta general distributions are described as $\beta(\alpha_1, \alpha_2, \text{A}, \text{C})$.
- Pert distributions are also used since it is a mix of triangular and beta distributions. The type of distribution is slightly more intuitive to use then the beta distribution and it is more sensitive to the most likely value than the minimum and maximum values, compared to triangular distributions. Pert distributions are described as Pert(A, B, C).

In the Tables E.4 and E.5 the distributions are presented (when applicable) twice, both as X(Y) and as (B D/E) where applicable.

4.4 Data Processing

For data processing Microsoft Excel 2003 has been used together with the macros provided in Palisade @Risk v 4.52. All distributions are defined and linked to one separate sheet from the actual risk model (i.e. the event tree). This gives the possibility to use the same output where the nodes are to be the same. For the final results a Monte Carlo simulation with 10,000 iterations was made. The program provides detailed statistical information for both the input and output data.

5 Hazard Identification

The aim of the hazard identification is to determine the main risk contributors to be considered in the following risk analysis. In order to estimate the risk of a fire or explosion in the machinery space data from several different sources have been weighted together. The information is mostly taken from and based upon a NK (1994) report, data from the OREDA (2002) handbook, a USCG (1998) investigation as well as a Thesis Database Search based mostly on GL classed ships. Even though the sources above, with the exception of the Thesis Database Search, are rather old given the limitations regarding ship age they are considered relevant due to limitations in the information available on this subject.

The outline of this chapter is first to describe the sources and findings in order of their importance for the final conclusion, and then follows an evaluation together with a sensitivity discussion/analysis of the same.

5.1 Thesis Database Search

When identifying previous incidents with respect to fire and/or explosion in the machinery space three different databases have been used. The search has been done with limitations regarding ship age (described below) as well as the ship type. For the selection of the ship type the classification provided by the LRF (2009*b*) database, Statcode5, was used (see Section 2.3.1). The three databases overlap to a certain extent and sometimes contain the same incidents and the level of detailing on each casualty description also varies to some degree. The databases are as follows:

- Germanischer Lloyd Damage Database Version 1.3
- Lloyd's Register Fairplay (LRF)
- National Technical University of Athens (NTUA)

All three databases have been searched for ship fire and explosion incidents to gather as much information as possible. Due to all databases having unique characteristics, containing different types and amounts of information and having different search functions, they have been approached in slightly different ways, as described in further detail below. Table 5.1 provides information of the number of entries collected and finally used from each database respectively.

Table 5.1: The databases from which relevant casualties reports have been found

Database	Total entries	Collected	Relevant	Final (Fire/Explosion)
GL	4639	719	45	14/2
LRF	10,971	34	20	9/4
NTUA	1294	87	0	0/0

Limitations Regarding Ship Age

Only ships delivered 1998 or later have been considered within this thesis when going through casualty data but also when it comes to regulations and safety requirements. This cut has been made for various reasons, the following being the most important:

- As shown in Section 3.1 the world fleet of both oil tankers and container vessels is fairly young, with 33% of the tanker fleet and 52% of the container fleet being eleven years of age or younger. For the GL fleet the corresponding percentages are 38% and 69% for tankers and container vessels respectively. (LRF 2009*b*)

- The SOLAS regulations (see Section 2.2.1) are constantly being revised to suit the current needs and adopt to new findings and innovations for safer maritime transport. With some exceptions the new regulations generally apply only to ships constructed after a certain date when the new regulations come into force, resulting in a world fleet that is not necessarily homogeneous when it comes to fire safety. Since a new version of SOLAS was introduced in 1998 all ships of interest in this thesis must comply with no less than these requirements.

- One of the ambitions with this thesis is not only to give a historical overview of the greatest fire and explosion risks in the machinery space, but also to look ahead to see what might be done in the future to reduce risks. The average operating time of a ship (from delivery date to scrap date) is approximately 26.4 years for container vessels and 23.7 years for oil tankers (LRF 2009*b*). For this reason it was considered suitable to look mainly at the newer ships that will still be operating in the next few decades, rather than focus on the older ships in the world fleet, whose technical systems and installations might be outdated in the future.

Germanischer Lloyd Damage Database

This database contains all incidents reported on GL classed ships. Together with documentation such as service statements, e-mail conversations and other documents available in the internal document database (GL 2009*c*) it was possible to get a better picture of the incident rather than relying on the information from the database alone.

When reviewing casualty data the decision was made to include cable fires in the analysis even though they have sometimes self-extinguished before spreading beyond the start component and have not always led to fully developed fires. This decision was mainly based on the danger for the crew in connection to cable fires and the toxic smoke it often produces. Furthermore this type of combustion often results in smouldering fires that produce a lot of smoke that damages the equipment which in turn may require extensive cleaning of the entire machinery space. Cable fires also implicate a major risk of developing into large fires if left unattended, due to the heat and smoke produced.

To get a wide search and include all relevant incidents, all reported ship accidents in the machinery space area relating to fire, explosion and/or overheating damages, as well as consecutive damages thereof, were considered initially. This resulted in 719 hits in total, after which the result list was revised to remove doubles and other non-relevant entries. The two main characteristics used to sort out the relevant entries were the ship type as well as the age of the ship. As per the objectives of the thesis only oil tankers and container vessels are of interest. After manually going through the damage descriptions 45 incidents were left to be examined in more detail.

Lloyd's Register Fairplay

The database is published and maintained by LRF. In addition to a database covering individual ship characteristics on the current world merchant fleet, information is provided on reported incidents and accidents. (LRF 2004)

The following data is provided in the casualty database accessed at GL, according to the contract between GL and LRF:

- All serious and non serious incidents subsequent to 31 December 1989.
- Ships of LRF Statcode 5 Level 2 Category (tankers, bulk carriers, dry cargo/passenger ships).
- Ships built later than 31 December 1979 and with a GT of 1000 and above.

An initial search for all reported fire and explosion casualties on board ships resulted in 497 hits in total. After selecting only incidents on board oil tanker and container vessels, and considering only those ships that are up to eleven years old 34 entries remained for further examination. In the case of double entries with respect to findings in the GL Damage Database the actual information on the incident has been transferred but the incident has been counted as originating from the GL Database. This resulted in 20 relevant entries from the LRF database.

National Technical University Of Athens

This Tanker Incidents Database has been setup by the Ship Design Laboratory (SDL) of National Technical University of Athens (NTUA). The database was setup in the framework of the EU founded project *POllution Prevention and Control - Safe Transportation of Hazardous Goods by Tankers* (POP&C), a project to prevent maritime oil spills, in order to make a review of AFRAMAX tankers incidents. (AFRAMAX is a class of tankers with DWT of 80,000 - 119,999). (Alissafaki et al. 2006)

Alissafaki et al. (2006) have performed a *Critical Review of AFRAMAX Tanker Incidents*. The basic information on incidents of their concern were mostly originating from the LRF database covering years 1978-2004. With respect to the size and specific subtypes of tankers of their interest, 1294 records were found. It is from this set of records that 87 incidents tagged with fire/explosion were found for this thesis. Out of these entries only 2 were considered relevant, e.g. a fire originating in the machinery space of a ship of less than eleven years of age. However, these two incidents were also found in the LRF database search. Given these circumstances the NTUA database did not provide any new information and was therefore excluded from further analysis.

5.1.1 Incident Selection

After the initial selection of 67 incidents a more detailed investigation on each incident was made. Information on the incidents was mainly found in GL's own documents such as service statements, incident reports or e-mail communication regarding the incident. In some cases a search on the internet was made to gather more information. Although the information was sometimes lacking in detail the incidents were sorted into three groups: fire, explosion and other. In cases where it was not clear whether or not there had actually been a fire and/or explosion or if it had occurred in the machinery space various persons at GL were consulted (see Appendix G). Based on these consultations it was determined whether some incidents (i.e. overheated components) could potentially lead to a fire and/or explosion or just to a mechanical breakdown.

10 incidents were established to have started outside the machinery space and were not considered for further analysis. The remaining 55 incidents were as follows:

1. Fire (23):
   All incidents where a fire had actually occurred were categorised in this group. For example most of the incidents involving electrical failure (e.g. where cables were burnt) fit here. Smouldering cables have a great risk of breaking out into an actual fire with open flames and furthermore produce a lot of toxic smoke.
2. Explosion (6):
   This group consist of incidents where it was stated that an explosion had occurred.
3. Other (26):
   Incidents in this group were often mechanical failures with a low possibility of developing into a fire or explosion, or alternatively where damages due to e.g. overheating that potentially could lead to an explosion had been confirmed. Most of these incidents involve heat damage to the boiler where the plates have experienced deformation. All these incidents were taken out from further numerical calculation but kept as indicators on where failures in the machinery area could occur.

5.2 Other Data

Due to insufficiencies in the information found in the incident reports other sources had to be consulted, these are presented below.

5.2.1 Nippon Kaiji Kyokai Report

In the report by Nippon Kaiji Kyokai (NK 1994) survey reports on 73 ships with cases of engine room fires out of 6000 NK classed ships from 1980 to 1992 were investigated in order to identify the most common causes and possible counter measures.

It was found that 0.1% of the NK classed ships were damaged by engine room fires during the 13 years covered. About 75% of all fires occurred when the ship was underway, out of which 52% of the ships suffered such damages that they became unnavigable. No correlations were found between the number of fires and the ship's age or GT. The main sources of fire were fuel oil piping at the main engine, generators and main switch board, as well as fuel oil piping of the boiler. Out of these fires 25% resulted from lubrication oil piping. The fires above are generally caused by leakage due to vibrations. The most common cause of fires resulting in unnavigable conditions were electric failures in the main switchboard or main electric cables due to igniting of fuel/lubrication oil.

With respect to consequences it was found that, out of the 73 cases, an average of 1 person was killed every year and another person injured. The extent of financial/property damages was not reported in detail. However it was noted that most ships were able to return to service within one to three weeks of the fire. After the SOLAS requirements concerning fire protection for hull and electric cables coming into force 1984 no engine room fires were reported to extend into hull compartments.

Certain high-risk areas were identified, mainly areas where fuel piping connects to main engines and generators, oil burners of boilers, exhaust gas pipes, turbochargers and main switchboards. Various safety measures are proposed to prevent or reduce the effects of machinery space fires. Several recommendations focus on separating fuel and lubricating oil from hot surfaces, and ensuring that insulation in critical areas (such as exhaust gas pipes and turbocharger) is restored correctly after inspection or maintenance work. Since vibration is a major contributor to leakage in fuel piping it is suggested that both design and construction of pipe fittings should be improved. Furthermore measures are recommended to reduce the risks of cable fire, given that they both produce toxic smoke which induce great risks on the crew, but also is the prime cause of loss of propelling power. To take the layout of the machinery into account as well as laying electrical cables on or underneath the generator flat rather than on the upper ceiling are two proposed ways of reducing the risks. Finally, regular inspections on electrical installations and regular cleaning of areas where soot and sludge accumulate are proposed, as well as stricter safety procedures prior to and during maintenance work.

The investigation presents some data on fire detection and extinguishing, suggesting that 81% of the fires were detected by means of the crew, either visually noticing smoke or flames (80%) or by hearing abnormal sounds (1%). In the remaining cases, 19%, the fire was detected automatically. This was partly believed to be the result of the majority of fires occurring in daytime. As for extinguishing fires the data show that 40% of fires were extinguished by portable equipment (CO_2, foam or dry chemical) and 18% by the fixed CO_2-system. Another 20% were extinguished by sea water whereas the remaining 20% burnt out naturally or with the help of a fire-fighting vessel.

Finally the extinguishing time, including the selected fire extinguishing method, was investigated. Results show that the vast majority of fires were distinguished within one hour (41% within 30 minutes and another 51% between 30 and 60 minutes). It was also noted that portable equipment is most common in the early stages, after which fixed CO_2-systems, sea water and eventually fire fighting vessels take over. (NK 1994)

5.2.2 Failure Rates From the OREDA Handbook

The Offshore Reliability Data Handbook (OREDA 2002) provides reliability data for offshore equipment collected by eleven oil companies. Although offshore plants and equipment are not identical with a ship's components the information can provide some information on failure rates. Furthermore in both cases (offshore and machinery spaces aboard of ships) the systems mostly distribute the same fluids.

For every group of components there are numbers regarding different failures presented for the group as well as for specific sub categories. The failure rate function used tells how likely it is that an item that has survived up to time t will fail during the next unit of time. So the failure rate function used is a function of time and divided into different modes of failure. It is defined as follows (OREDA 2002, p. 40)

> **Failure**
> *The termination or the degradation of the ability of an item to perform its required function(s). It includes:*

- *Complete failure of the item,*
- *Failure of part of the item that causes availability of the item for corrective action,*
- *Failure discovered during inspection, testing, or preventive maintenance that requires repair, and*
- *Failure on safety devices or control/monitoring devices that necessitates shut-down, or reduction of the items capability below specified limits.*

It is clear that there are a lot of failure modes included that are not of interest for this thesis (e.g. noise, vibration or abnormal instrument reading). In order to find out the failure rate of interest (i.e. overheating or leakage) the numbers of failures together with a percentage of failure mode and the *aggregated calendar time in service* for the specific components were used. The boundary conditions for each group of components are given in the handbook but are in general defined as parts associated with the generic items that are considered to be essential for its function. For example the power transmission (e.g. gear) is included for a pump while the driver (e.g. electric motor) is not. This level of detail exceeds the needs for this thesis and would be hard to handle in combination with other uncertainties, so the boundary conditions as well as other detailed information, are not taken into consideration.

Three main steps (described below), that each introduces some limitations to the model, were used in concluding the failure rate; at first a choice of which components to use, secondly how often these components leak oil and finally an estimation of the probability of a hot surface/ignition source being close enough to a leak. Specific numbers for components and estimated factors used can be found in Tables 5.4 and 5.3. These values are an average representation of the distributions used in the sensitivity analyses, actual distributions used can be found in Tables E.1 and E.2.

Components

The components chosen to be included in the model (i.e left hand side of the *bow tie*, see Chapter 4) were based on interviews made, such as Ionel (2009) and Zalevski (2009), findings in the database search and the report by NK (1994). Following components were included (subgroups in brackets); pumps (oil handling), boiler (all), generator (diesel gas motor), main engine (combustion), separators (all) and valves (all). In the case of valves these were not extracted from above sources but included due to the reasonably high probability of leakage and that there would be a significant number of valves handling oil in a machinery space.

Since the failure rates were given in frequencies for failure per single component an estimation had to be made of how many of each component there are in a generic machinery space. For boilers, generators and the main engine a number that is commonly expected on a normal ship was used. Since it turned out that pumps were by far the biggest source of leakage, the quantity was estimated by taking an average number from ships found in our database search for incidents, using the Ship Information System (SIS 2009). The same method was used for the number of separators. In the case of valves an estimation was made by counting the number of valves on *M/S Thesis*. It was found that every oil system present in the machinery space (heavy fuel oil, marine diesel oil, lubrication oil, thermal oil) consists of an average of 75 valves. Therefore a number of 300 valves was used.

Ignition Source

The information on failures that have occurred due to overheating is not so useful in this thesis, mostly for two reasons; One is that the failure rate only tells if a failure was compelled by a temperature that exceeds the component's running temperature (by a given range). Many of these incidents would therefore not contribute to a fire since the temperature could be well below the actual temperature of the fuel oil itself. (Fuel oil needs to be heated up to approximately 100-120°C in order to reach the required viscosity for purifying to keep water and dirt particles from passing the injectors and to meet the viscosity requirements at the main engine (van Dokkum 2003).) Secondly there are components in the machinery space that are working with high temperature from the beginning and need not to have a *failure* in order to pose as ignition source for fire. For example parts of the main engine surface reach up to 400-450°C (Ionel 2009) under normal conditions. Table 5.2 provides minimum ignition temperatures for different types of marine fuel in contact with hot surfaces. Furthermore a lot of pipes and other components are required to be isolated to prevent fire in case of a oil leakage on it, even under normal running conditions.

Table 5.2: Minimum temperatures of surface where ignition of fuel was observed (values estimated from figure from (Ito et al. 2006)) In the tests fuel drops (volumes of 0.1-0.7 cm^3) were dropped on isolated pipes.

Type of Fuel	Temperature [°C]
Turbine oil	445
Gas-oil	330
Marine Diesel Oil*	385
Heavy Fuel Oil	420
Lubrication Oil	455

* The fuel tested is slightly different from Marine Diesel Oil according to ISO. However it is considered equal for the purpose of this thesis.

Given these problems with application of overheating failure for components, another approach had to be taken. With *M/S Thesis* as a model some assumptions were made. From drawings of the machinery space it was concluded that the floor area is consisting of three floors of 750, 750 and 450 m^2 each, with total area of 2000 m^2. Given that the height of each level is 3 m, this is fairly accurate with the total volume of the space being 5821 m^3 according to GL (1995). Assuming that the hot surfaces as well as the leaking components are evenly distributed over the space an estimation can be made on the probability of a leakage big enough to start a fire occurring at the same time as a source of ignition.

As noted earlier there are a lot of hot surfaces in a machinery space, and a *Hot Surface Factor* (i.e. the part of the space assumed covered by hot surfaces) of 0.05 results in 33 m^2 on each floor, which is considered reasonable. This number was then reduced to 0.025 due to physical barriers such as shields and isolation on pipes etc. being in place. Since not all fires are ignited by a hot surface the final number is multiplied by an *Other Ignition Source* factor of 1.08. This is mainly based on the USCG (1998) investigation stating that 93% of all fires were ignited by a hot surface and the rest by electrical spark, explosion or other. The two factors used can also be found in Table 5.3.

Leakage

Information about various kinds of leakages for components is provided within the handbook, i.e. external leakage of the process/utility medium, internal leakage, leakage in closed or open conditions (for valves). All these leakages for a specific component were summarised to provide an estimation of the failure rate on a single component. The calculated and converted values (from frequency/10^6 hours to frequency/year) are shown in Table 5.4. These factors are adjusted to match a generic machinery space.

Not all of the leakages that lead to a failure according to the definition in the handbook will lead to a leakage that can ignite. It is reasonable to assume that even small leakages that drop would be included in the failure rate, or even at places where there is no danger of ignition. An assumption was made that 1/100 failures due to leakages will be big enough to ignite and cause a fire and therefore a *Critical Leakage Factor* of 0.01 was used. This assumption is similar to the assumption of injuries/fatalities as in Section 6.2.1.

Table 5.3: Estimated factors used in leakage failure based on the OREDA (2002) handbook and USCG (1998).

Factor	Value
Critical Leakage	0.010
Hot Surface	0.025
Other Ignition Sources	1.275

Table 5.4: Failure rates for leakage based on numbers found in the OREDA (2002) handbook and estimations.

	Frequency [/year/component]	Number of Components [Average from SIS (2009)]	Frequency [/year]
Pumps	1.22	18.0	22.0
Boiler	0.18	2.7	0.5
Generator	0.01	3.3	0.0
Main engine	0.31	1.0	0.3
Separators	0.16	6.0	1.0
Valves	0.07	300.0	21.5
TOTAL number of failures due to leakage per year			45.30

5.2.3 US Coast Guard

The investigation is based on incident records of oil spray fires from several sources: the US Coast Guard, The US Marine Safety Information System, Lloyd's Maritime Information Services Ltd, Nippon Kaiji Kyokai, The Transportation Safety Board of Canada, the Marine Incident Investigation Unit, Inspector of Marine Accidents Australia and the US National Transportation Safety Board. A total number of 182 incident records were reviewed, out of which 143 resulted in fires due to released fuel oil/lube oil in the engine room of ships. The incident investigated include tanker and container vessels as well as other vessels, e.g fishing and Ro-Ro vessels. This fact had to be considered when evaluating the results taken from this report.

Several conclusions were drawn from the investigation, and even though the causes of each incident varied the following categories of general failure causes were found (within brackets is the percentage of a specific cause out of the total number of fires):

1. Unknown root cause (30%),
2. Personal error during inspection or maintenance (25%),
3. Design, manufacturing or installation deficiencies (20%),
4. Lack of adequate inspection or maintenance (10%),
5. Personal error and/or equipment failure during preparation for inspection/maintenance to service after inspection/maintenance (10%), and
6. External impact (5%).

Furthermore it was noted that hot surfaces were the sources of ignition in 93% of all fires and 86% of all fires resulting in fatalities. The oil spray itself came in almost 40% of the cases from skid piping, tubing or hose for diesel engines, turbochargers or boilers (usually under the control of the manufacturers). The most common, 55%, sources of fatal spray fires were duplex strainers, filters or coalescers. Another finding was that whereas the fuel oil system is responsible for about 70% of the fires (with the lubrication oil system is responsible for the remaining 30%), the lubrication oil system contributed to 50% of all fatal fires. No correlation was found between the number of fires and ship's age, size, type or nationality.

As far as consequences are concerned the investigation came to show that (for the 57 cases where damages were documented) the ship sank in 10% of the cases, suffered a constructive total loss in 16% of the cases and in the remaining incidents contracted average damages of about 293,000 USD. Unlike previous recommendations the investigation did not show that oil mist detectors in the casing of the engine would effect the outcome of the incidents (neither with respect to preventing nor mitigating safety related fires).

The investigation resulted in 18 recommendations, involving both technical and management issues, on how to ensure the safety within the machinery space. Most recommendations involve isolating the fuel from hot surfaces, but other safety measures such as establishing operation guidelines, reviewing maintenance programs and design/installation specifications for fuel oil/lube oil systems and facilitate escape by providing readily accessible emergency breathing apparatus are also suggested. (USCG 1998)

5.2.4 Fire On Board by Rushbrook

The data being analysed by Rushbrook (1998) in the book *Fire On Board* cover incidents for a 20-year period from 1977 to 1996 and has been collected from the Liverpool Underwriters Association (1977-1985) and the Institute of London Underwriters (1985-1996). Although this source is not directly used to quantify the probability of fire it has been a source of information during the process and is therefore summarised here.

For ships in general is noted that most fatalities occur in the engine room. However, for tankers the numbers are somewhat uncertain since there are many fatalities whose locations are unknown. Furthermore a large portion of tanker deaths occur in the tanks as well. Given that the number of incidents in container ships is limited it is difficult to come to specific conclusions. After analysing the fire locations for total and partial loss fires it is noted that the probability of more serious fires is greater in the machinery space compared to other locations on the ship, with about a third of all serious fires starting in the machinery space. Unlike USCG (1998) and NK (1994) (see Sections 5.2.3 and 5.2.1) Rushbrook (1998) concludes that the number of fires is highly dependent on the ship's age. It is noted that the probability of fire, as well as the proportion of fires resulting in major damages, is increased in the 10 year period between age 15 to age 24 in the ship's operating age.

A more in-depth analysis of machinery space fires was made for years 1991-1993, showing that almost 54% of all ship fires started in the machinery space. Similar to the investigations by USCG (1998) and NK (1994) it was noted that most fires were initiated by explosions or from uncontrolled release of flammable vapours or fuel in the engine room. These fires are also presumed to induce major risks of crew injuries or fatalities. Furthermore it is noted that 60% of engine room fires cause major damages, and usually required the ship to be towed back to port.

5.3 Evaluation

The following subsections provide an analysis of each of the four sources and explanations on how the calculations were carried out. The results are summarised in Tables 5.5, 5.6 and 5.7. Findings in the different frequency rates were weighted together with factors based on the applicability and reliability of each source for this thesis based on the different backgrounds and assumptions that apply for each source. The individual frequency rates and weight factors are presented in Table 5.8.

5.3.1 Thesis Database Search

The 29 incidents found in the database search were analysed individually and categorised based on the fire source, to identify the most critical components and their failure rates as well as to calculate an expected value of the likelihood of a fire or explosion occurring.

The analysis showed that generators posed a fairly large risk, amounting to 31% of the incidents. A closer investigation indicated that these fires usually started due to electrical failures or oil/fuel leaks. Boilers proved to be another large risk, with 14% of fires starting due to boiler explosions or oil/fuel leakage in the vicinity of the component. Further fire sources were the main engine, pumps, as well as electrical failures in the main switchboard or turbocharger. With respect to general cause types electrical failures together with oil/fuel leakage dominated the statistics (representing 41% and 14% of the cases respectively). However, the details for a fairly large part of the incidents are unclear and hence the fire causes were unknown in 35% of the cases.

When taking all fire/explosion incidents into account it was found that the total fire/explosion frequency given the reported casualties amounted to approximately 1.17×10^{-3} incidents per shipyear. The calculations on shipyears is described further below. More detailed data on the failure frequencies are presented in Table 5.5.

Shipyears

The calculations on the total number of shipyears (i.e. the total time in service for all ships constructed and active between 1998 and 2009) relevant for the Thesis Database Search was based on the registered delivery date for each individual ship in the LRF Database

(LRF 2009*a*). It was assumed that the relevant data, i.e. ships with Statcodes as stated in Table 2.1 constructed 1998 or later, in the LRF database represent the same ships that are the basis of the Thesis Database Search for fire/explosion incidents. Therefore it is assumed suitable to use the age of those ships, approximately 2500 oil tankers and 2500 container vessels, as a basis for the expected incident frequency calculations.

Each ship's time of service was defined as the time from delivery date until scrap date or alternatively until 1 January 2009. This results in 11,916 shipyears for oil tankers, 12,898 shipyears for container vessels and a total of 24,814 shipyears for the entire fleet of interest.

Table 5.5: Frequencies for fire incidents, the starting components as well as the type of cause, based on the Thesis Database Search. The table includes the scenarios represented in the statistics. Hence scenarios that were not represented in the database search, including components/types of causes not found to have been the main cause of fires, have been left out of the table.

Source of Fire (Component)	Number of Incidents	Frequency [10^{-5}/shipyear]	Percentage of All [%]	Type of Cause	Number of Incidents	Frequency [10^{-5}/shipyear]	Percentage of All [%]
Boiler	4	16.1	13.8	Explosion	2	8.1	6.9
				Oil/fuel	1	4.0	3.5
				Unknown	1	4.3	3.5
Generator	9	36.3	31.0	Electrical	5	20.2	17.2
				Oil/fuel	2	8.1	6.9
				Unknown	2	8.1	6.9
Main engine	2	8.1	6.9	Explosion	1	4.0	3.5
				Oil/fuel	1	4.0	3.5
Pumps	1	4.0	3.5	Electrical	1	4.0	3.5
Switchboard	2	8.1	6.9	Electrical	2	8.1	6.9
Turbocharger	1	4.0	3.5	Unknown	1	0.0	3.5
Other/ Unknown	10	40.3	34.5	All	10	40.3	34.5
TOTAL	29	116.9	100.0		29	116.9	100.0

5.3.2 OREDA

As a sensitivity analysis the values used in the model from the OREDA (2002) handbook were given distributions and then simulated with a Monte Carlo simulation to give an interval of frequencies of fires in the machinery space and also to indicate which factors are the most critical.

All numbers found were fitted with triangular distributions with the given value as the most probable and minimum/maximum as ±10%. For the actual number of components an estimation of the most probable value was made, as described in Section 5.2.2, and these were also put as triangular distributions with the mean value as most probable and minimum/maximum as the extreme values found in SIS (2009) for the ships of interest. For the number of valves a count was made with the help of drawings of *M/S Thesis*, with the conclusion that the numbers of valves in the oil/fuel systems (i.e. heavy fuel oil, marine diesel oil, lubrication oil and thermal oil) were between 50 and 100 (with a most probable value of 75). A complete list of distributions can be found in Table E.2.

The three factors (critical leakage size, hot surface and ignition source) used were also defined as distributions. For the *Critical Leakage Factor* a value of ±50% and for the *Hot Surface Factor* ±60% were used. For both factors a uniform distribution was used (i.e. U(0.005; 0.015) and U(0.01; 0.04) respectively). For the *Other Ignition Source Factor* a distribution from USCG (1998) was used. The investigation of 143 fires showed that 93.3% were ignited by a hot surface. However, when looking at a more detailed description of the ignition source data and excluding fires where the ignition source was categorised as *Not Stated* 68% of fires were noted to be related to hot surfaces. Since the failure modes of concern from the OREDA (2002) handbook only involve oil leakages, similar to the USCG (1998) investigation, a uniform distribution for the *Other Ignition Sources* was defined, with values within the range concluded by USCG. In summery the *Other Ignition Factor* was set as U(1.08; 1.47). A complete list of distributions for these factors can also be found in Table E.1.

5.3.3 Nippon Kaiji Kyokai Report

The report is based on 73 fires occurring on NK classed ships between 1980 and 1992. (NK 1994) However out of the 73 fires only 66 incidents are relevant for this analysis.

Similar to the Thesis Database Search the investigation concluded that generators was the most common fire start component (21% of the fires). This was however followed by failures in the main engine (17%) and switchboards (12%). In addition to the above mentioned there are various components known as being the main source of engine room fires. With respect to the type of failure the data show that fuel/oil leakages were involved in 48% of the incidents, followed by electrical failures (18%). More detailed data are presented in Table 5.6.

When summarising the casualty data, assuming that the affected ships were representative of the entire NK fleet of around 6000 ships, a total frequency of 1.03×10^{-3} fires/explosions per shipyear was calculated. More information on the calculation of shipyears is presented below.

Unlike the Thesis Database Search however, the NK (1994) report include all types of ships in its analysis which may explain some of the differences in the results. Given that the NK report describes fires between 1980 and 1992 there are also some differences in the fire protection systems in place.

Shipyears

Information on the age of every ship investigated is given in the NK report, with ship ages ranging from 1 to 25 years and with an average age of 10.6 years. These data were then used to calculate the total age in shipyears of the fire affected ships. According to the report the NK fleet consisted of around 6000 ships at the time of publication of the report, and since the ships investigated included all types of vessels it was assumed that the ships investigated were representative of all ships in the NK fleet. Based on these assumptions it was noted that the total age for the NK fleet was approximately 64,000 shipyears. This number was finally used to derive the total expected frequency for fire/explosion in the machinery space of NK vessels.

Table 5.6: Frequencies for fire incidents, the starting components as well as the type of cause, based on fire incidents on NK classed ships between 1980 and 1992. The table includes the scenarios represented in the statistics. Hence scenarios that were not represented in the investigation, including components/types of causes not found to have been the main cause of fires, have been left out of the table. (NK 1994)

Source of Fire (Component)	Number of Incidents	Frequency [10^{-5}/shipyear]	Percentage of All [%]	Type of Cause	Number of Incidents	Frequency [10^{-5}/shipyear]	Percentage of All [%]
Boiler	6	9.4	9.1	Oil/fuel	6	9.4	9.1
Generator	14	21.9	21.2	Electrical	2	3.1	3.1
				Oil/fuel	12	18.8	18.2
Main engine	11	17.2	16.7	Oil/fuel	11	17.2	16.7
Pumps	2	3.1	3.0	Electrical	1	1.6	1.5
				Overheating	1	1.6	1.5
Separator/Purifier	2	3.1	3.0	Electrical	1	1.6	1.5
				Oil/fuel	1	1.6	1.5
Switchboard	8	12.5	12.1	Electrical	8	12.5	12.1
Turbocharger	7	11.0	10.6	Explosion	5	7.8	7.6
				Oil/fuel	2	3.1	3.0
Other/ Unknown	16	25.1	24.2	All	16	25.1	24.2
TOTAL	66	103.4	100.00		66	103.4	100.00

5.3.4 US Coast Guard Investigation

The USCG (1998) investigation on oil spray fires is based on casualty data from various sources. Given that is has not been specified what total number and types of ships that were used to collect the data, a total frequency of the likelihood of fire/explosion in the machinery space has therefore not been calculated. Furthermore the investigation only includes fuel oil/lube oil spray fires and does not look into other potential fire sources in the machinery space. Similar to the NK (1994) report the ships included are not limited to oil tankers and container vessels, but represent all ship types. The data have however been used to get an indication of the most common fire sources and has been seen as a means of judging the reliability and credibility of the other sources.

The investigation focuses on two factors; the source of the oil leakage is listed as well as the source of ignition. The undoubtedly most common sources of ignition amount to approximately 68% (*Hot surface (other), Open flame, Turbocharger and Steam line*). With respect to the source of oil leakage vents/pipes are the most common failure components (62% of the total) followed by other/unknown components (26%). Given that the investigation had a somewhat different approach than the other sources, and that the fire incidents have been categorised in a slightly different way it is hard to compare the findings directly. More detailed data are shown in Table 5.7.

Table 5.7: The most common sources of ignition as well as sources of oil leakage, by percentage of all investigated oil spray fires in the machinery space. The tables include the scenarios represented in the statistics. Hence scenarios that were not represented in the investigation, including components/types of causes not found to have been the main cause of fires, have been left out of the tables. (USCG 1998)

Source of Ignition (Component)	Percentage [%]
Boiler	0.7
Explosion (other)	2.1
Hot surface (other)	52.5
Open flame	4.9
Spark	1.4
Steam line	2.8
Turbocharger	9.1
Other/unknown	26.6
TOTAL	100.0

Source of Oil Leakage (Component)	Percentage [%]
Main engine	4.0
Pumps	4.0
Separator/Purifier	1.1
Turbocharger	1.7
Vents/Pipes	61.7
Other	17.7
Unknown	9.7
TOTAL	100.0

5.4 Summary

This section describes the findings regarding the incident frequency rate and hazard identification from the different sources used.

5.4.1 Incident Frequency Rate

The frequency of fire and/or explosion in the machinery space of oil tankers and container vessels is 2.50×10^{-3} per shipyear.

In order to conclude this a combination of three sources has been weighted together (see Table 5.8). Note that it was impossible to derive a frequency from the USCG (1998) report since the exact number of ships and shipyears was not provided for the incidents investigated. Instead it has been used to determine sources of fire and the contributing components.

Since the findings in the Thesis Database Search are based on a selection of ships of interest this number is put as the most significant. The two others, i.e. from the NK (1994) report and the OREDA (2002) handbook are used as complementary information and are considered less significant. The NK (1994) report is believed to be the second most reliable due to the fact that it investigated engine room fires in general and that it is based on statistics of actual incidents. The numbers from the OREDA (2002) handbook come with a lot of assumptions which results in a relatively high number for the frequency of fire in machinery spaces. The fact that it gives a number believed to be quite high and that there are a lot of uncertainties tied to the number, it is considered the least significant for the final result.

5.4.2 Critical Components

A comparison between the Thesis Database Search, the NK report (1994), the OREDA statistics (2002) and the USCG investigation (1998) show that the results vary somewhat when it comes to the most critical components with respect to fire/explosion in the machinery

Table 5.8: The calculated frequency values from different sources, in shipyears, and the contributing weight factor for the final result. The sources were given different weight factors depending on their expected reliability and relevance for this thesis.

Source	Value	Weight
Database Search	0.0012	0.6
NK	0.0011	0.3
OREDA	0.0144	0.1
TOTAL	0.0025	

space. The four sources have different approaches to a certain extent but there are some common indications of failure prone components.

The OREDA (2002) statistics as well as the USCG investigation (1998) both provide data on components prone to fuel/oil leakage and show that pumps and piping (pipes, vents and valves) account for the majority of leaks (66% and 96% according to the USCG report (1998) and the investigated OREDA statistics respectively). It is however to be noted that the OREDA statistics is based on selected components considered relevant for this thesis, and therefore a complete record is not presented. Other components such as separators, the main engine or turbocharger can occasionally cause a fuel/oil leak (according to the USCG report these components represent between 1% and 4% of the leakages each). All types of leaks are often, in close to 70% of the cases (USCG 1998), ignited by hot surfaces (e.g. piping, other machinery etc.).

The Thesis Database Search and the NK (1994) report are both based on actual fire/explosion incidents and provide information on the start component of the fire/explosion, though not specifically separating the source of the fuel from the source of ignition. It is however noted that in both cases the generators are the most common source of fire (accounting for 31% and 21% of the incidents respectively). The sources differ somewhat with respect to other components. Whereas the Thesis Database Search suggest that boilers compose a major risk (14% of the incidents) the NK report (1994) indicate that the main engine (17%), switchboards (12%) and turbochargers (11%) are more critical components.

When looking at the types of causes the Thesis Database Search show that electrical failures account for most of the incidents (28%), followed by oil/fuel leakages (14%) and explosions (10%) whereas the NK report (1994) suggest that oil/fuel leakages are the main source of fire (49%), followed by electrical failures (18%), explosions (8%) and overheating (2%).

In summary the results vary, not surprisingly, depending on the source with respect to the most critical component and the main causes of fire. Even though the incidents may be categorised differently depending on the level of detail reported on the fire, the interpretation of the casualty reporting and the purpose of the investigation it seems as though oil/fuel leakages together with electrical failures are responsible for most fires. When it comes to oil/fuel leakage the pumps and piping together with the main combustion machinery (generators and the main engine) are the most common sources. Electrical failures usually originate from the generators or switchboard.

6 Consequence Analysis

This section describes each of the risk model input variables on the right hand side of the *bow tie* (see Chapter 4, Figure 4.1) along with motivations for the values used.

6.1 Input Variables

The following sections describe the background information with respect to the probabilities used for the propagation/extinguishing of the fire, i.e. /Explosion/Fire/Detection/Portable/ Sprinkler/CO_2/Fire Fighting/ and the main assumptions in relation to the probability distributions.

Costs are described separately in Section 6.2 for *safety* and in Section 6.3 for *financial losses.* Table E.3 gives all distributions used for each node in the event tree and the actual distributions for probabilities and costs are found in Tables E.4 and E.5.

6.1.1 Explosion

In this thesis explosion is defined as (Frantzich & Holmstedt 2003):

> *Instantaneous combustion of a combustible gas mixture leading to rapid heat release or pressure rise, or alternatively a mechanical collapse of an enclosed container due to rapid pressure build-up and/or rapidly increasing volume.*

Only explosions as initiating events are of interest. If a fire occurs and an explosion follows the explosion is not taken into special consideration.

The estimation of the probability of explosion is based on the Thesis Database Search and on findings in the NK (1994) report. The share of explosions out of the total amount of incidents was found to be 6/29 and 6/66 in the two sources respectively and these values were was then weighted by the same proportions as in Table 5.8 (i.e. 2:1). An uncertainty interval of 20/20 was used, resulting in a triangular distribution of T(0.17 20/20).

6.1.2 Fire

Accidents that involve neither explosions nor fires are outside of the scope of the thesis. Hence there must always be a fire or explosion occurring in the scenario, and the probability for incidents in branch /0/1/-/-/-/-/-/, i.e. no initial explosion but a fire, must be equal to 1 (1 0/0).

For fires following an initial explosion the same sources were used as for explosion (NK 1994, and the Thesis Database Search). It was found that 0.83 of the explosion incidents were followed by fires, bringing the probability of a fire in node /1/1/-/-/-/-/-/ to T(0.83 20/20), the 20% interval considered reasonable due to some uncertainties in the statistical data.

6.1.3 Detection

In this thesis detection is defined as:

> *The time from point of ignition until the first person becomes aware of an incident, either by noticing smoke/heat/other signs of a fire and/or explosion, or after being brought to attention of an incident by means of an automatic alarm system. Detection is considered early if it occurs within 11 minutes of the ignition.*

The distinction between early and late detection is defined based on numbers found in Wong, Gottuk, Rose-Pehrsson, Shaffer, Tatem & Williams (2000), where 26 different tests were conducted to investigate the time from the point of ignition to detection for smoke detectors on ships. If only taking the average time for fires that are probable in machinery spaces into consideration a mean time of 8.5 minuets is given. The data include 5 tests with different fire scenarios with the following results (Wong et al. 2000):

- (MV_05) Flaming oily rags in a 6 l metal trash can, with an average detection time of $\overline{x} = 1.43$ min.
- (MV_08) Smouldering oily rags in a 6 l metal trash can, $\overline{x} = 30.84$ min.
- (MV_10) Flaming oily rags in a 6 l metal trash can, $\overline{x} = 1.82$ min.
- (MV_17) Flaming fuel oil in 11.4 cm diameter pan $\overline{x} = 2.79$ min.
- (MV_28) Smouldering cables, $\overline{x} = 5.58$ min.

The above resulted in a total average smoke detection time of $\overline{x} = 8.5$ min. Though there are large differences in the five scenarios the mean value is believed reasonable, based on personal experiences and discussions with experts, e.g. Ionel (2009).

According to the FSS Code (2007) a detection system has to give a general alarm throughout the ship if an indication of fire has not received attention by the crew within two minutes. When adding the 2 minutes investigation time to the 8.5 minutes a total detection time of approximately 11 minutes is given, which is considered to be the cut point between short and long detection time.

The number was found to be reasonable given the circumstances even though no other means of fire detection systems has specifically been taken into consideration. As described earlier (see Section 3.3.2) several different fire detection systems such as heat, smoke extracting or flame detection can be in use. The choice of focusing on smoke detection time was made since it is the most commonly used system whereas the other systems are usually not used uniformly throughout the machinery space and would only be used under special circumstances and/or as a complement to smoke detection.

The consequence model was set up to take three different detection times into account i.e. none, early and late. The distinction between early and late detection is described above. A non-existing detection would occur for example when there is a small fire that is not detected and self-extinguishes, leaving no significant damage. It was estimated that between 0% and 10% of the fires would be so small that they did not make any immediate damage and were not detected before they self-extinguished (/0/1/0/-/-/-/-/-/), with a distribution of U(0, 0.1). The assumption was made that any explosion would cause enough damage to be detected by some kind of failure indicating system on the ship, whether or not it is followed by a fire, e.g. by machinery failure or overheating indications even if not detected by a fire detector. For this reason an explosion followed by a fire will always be detected in the model and the distribution for /1/1/0/-/-/-/-/-/ was set to U(0 0/0).

The 11 minutes as distinction between the short and long detection time is based on an average time for smoke detectors. Since it is impossible to know exactly how long time that passes from point of ignition to detection for a real fire the distribution between the short and long time was calculated as half of the remaining incidents after subtracting the non-detected ones, with a 20/20 uncertainty interval.

6.1.4 Manual Fire Extinguishing With Portable Means

The definition of *manual fire extinguishing* in this case refers to a first fire fighting attempt by the crew by means of the portable extinguishers at hand in the machinery space. Hence, it does not include fully equipped fire fighters trying to extinguish the fire with the help of the water hoses and hydrant system on board. This is instead referred to as *fire fighting* in Section 6.1.7. Details of the SOLAS (2009) requirements can be found in Section 3.3.3.

Data from 60 machinery space fires, and the main means of extinguishing the fires, investigated in the NK (1994) report suggest that many fires are extinguished by portable means. 24 of the investigated fires, or 40%, were extinguished by CO_2, foam or dry chemical portable extinguishers.

It is however believed that the probability of a successful outcome of a manual extinguishing attempt is highly dependent on the detection time. A small fire is much easier to put out by hand than a fire that has been allowed to grow unattended for a longer period of time. An expected probability of 0.1 to successfully extinguishing the fire manually in the cases of *late detection*, events /0,1/1/2/1/-/-/-/-/, is therefore considered reasonable, equivalent to one fourth of the percentage share suggested by the NK (1994) report. This is assumed independent of whether the fire is preceded by an explosion or not. The uncertainty interval is set to 100% due to the figures being mere estimations and therefore more uncertain, resulting in a triangular distribution of T(0.1 100/100).

The two possibilities of *early detection* are unlike the events of *late detection* treated separately, since the growth phase of the fire is assumed to be rather different in the case of an explosion preceding the fire compared to a fire starting for other reasons. For fires preceded by an explosion, event /1/1/1/1/-/-/-/-/, the expected probability for extinguishing is assumed to be 0.2, i.e. lower than suggested by the NK (1994) report. An uncertainty interval of 100% is again used due to the probability being a mere estimation, resulting in a triangular distribution of T(0.2 100/100).

For fires with *early detection* where an explosion is not the initiating event, /0/1/1/1/-/-/-/-/, the reliability of manual fire extinguishing is considered significantly higher, and an expected probability slightly higher than indicated by the average rate indicated in the NK report (1994) is used. A triangular probability distribution with an expected value of 0.5 is therefore used. Given that it is believed unlikely that the successful rate much exceeds 50%, and if differing much believed rather to be lower the uncertainty interval is set to 30% and 10% below and above respectively, resulting in a triangular distribution of T(0.5 30/10).

6.1.5 Sprinkler System

All machinery spaces above 500 m^3 in volume on oil tankers and container vessels ships of 2000 GT and above, that were constructed on or after 1 July 2002, are required to have a *fixed local application fire-fighting system*. Further details on these systems and the SOLAS (2009) requirements can be found in Section 3.3.4.

Malm & Pettersson (2008) presents a comparison of international statistical data for the reliability of sprinkler systems. Given that the marine environment is more similar to an industrial environment than residential buildings only statistics from industrial buildings have been used within this thesis. The data is collected from incident statistics from Sweden (2006 to 2007), Finland (2004 to 2007), London/UK (1996 to 2005) and finally a more thorough analysis on Swedish incident statistics by Malm & Pettersson (2008). The reliability data from the different sources is presented in Table 6.1.

Table 6.1: The reliability of sprinkler systems in industrial buildings based on international incident statistics (Malm & Pettersson 2008).

Incident Data Source	Extinguished Fires [%]
Finland	17
London/UK	23
Sweden	45
Malm & Pettersson	64

Based on the variations in the effectiveness of the sprinkler system in the different countries a uniform distribution between the lowest and highest numbers (i.e. 17% and 64% respectively) was used, resulting in an average effectiveness of 40.5%.

Given that the sprinkler system is only a local application and does not cover the entire machinery space it has been assumed that the system can only influence the fire in 10% of the cases. This is considered reasonable with respect to the areas that are required to be sprinkler protected and the probability of a fire starting in one of those areas. Therefore the total probability of a sprinkler system extinguishing a fire has been reduced to one tenth, resulting in an average effectiveness of 0.0405.

Given that the sprinkler system can be released both automatically and manually the effectiveness of the system has been assumed independent of the fire detection time in that aspect that it is assumed that the sprinkler system is either manually released within the time of *early detection* or alternatively that it automatically releases by the heat of the fire. Since the sprinkler is located in the proximity of the machinery it is protecting, rather than spaced evenly across the entire machinery space it is assumed that the heat from a fire in any of the critical components will release the sprinkler system fairly quickly if at all. Hence the probability distribution of the sprinkler system succeeding is assumed to be the same in all scenarios, /0,1/1/1,2/0/1/0/0/0/, independent of whether the detection is *early* or *late*, resulting in a uniform distribution U(0.017, 0.064).

6.1.6 CO_2 System

An analysis of the reliability of CO_2 suppression systems based on 26 US Coast Guard incident reports involving machinery space fires was performed by Zalosh, Beller & Till (1996). The incidents investigated included oil spray (18 fires), electrical (3 fires), pool fires (2 fires) and other unknown causes (3 fires). The analysis showed that the CO_2 system extinguished the fires in 34.6% of the cases. The 9 cases where the CO_2 proved fully effective were all oil spray fires. Given that oil spray fires represented 70% of the investigated fires and that the other fire causes were only each represented in few cases, these variations in CO_2 efficiency have not been taken into account when setting the expected probability of successful extinguishing.

The NK report (1994) presents data on how 60 investigated machinery space fires have been extinguished and it was concluded that 11 out of 60 fires were extinguished by a CO_2 system. After subtracting the 24 fires extinguished by portable means, since manual fire fighting with portable extinguishers is assumed to always be the first fire fighting effort, it is concluded that the CO_2 system proved effective in 31% of the fires. This is also assuming that the CO_2 system is generally released before fire fighters enter the machinery space to extinguish the fire with help of the fire hoses and fire hydrant system, and that the CO_2 system is always released even in those cases where the fire has burned itself out. Furthermore, given that 99% of all ships are assumed to be provided with a CO_2 system (Busche 2009) it is assumed that the system was an option in all investigated fires.

Given that both of the two reports above came to similar conclusions on the effectiveness of the CO_2 system, it is considered reasonable to assume that such a system is likely to extinguish machinery space fires with an expected probability of 0.35. There are however some uncertainties; the NK (1994) report for example presents data from machinery space fires on several types of ships, not isolating larger vessels such as the oil tankers and container vessels of interest for this thesis. Furthermore the NK (1994) report includes accidents as early as 1980, and on ships up to 25 years of age. Given that the fire fighting requirements have changed over the years it can not be determined whether all ships involved were actually provided with a CO_2 system, which might bring its reliability to a higher number. The fact that the effectiveness of the CO_2 system might differ from both the size, the location, the fire cause and the type of fuel is seen as another source of uncertainty of the system's effectiveness. Therefore the probability of a CO_2 system completely extinguishing a fire is given an uncertainty interval of 20%. Given that both sources above indicate similar numbers for its reliability 0.35 is still seen as the most probable value. Hence, the reliability of a CO_2 system is given as a triangular distribution T(0.35 20/20). No distinction is made for the type of fire and the same distribution is therefore used for all scenarios, /0,1/1/1,2/0/0/1/-/-/.

6.1.7 Fire Fighting

Extinguishing by fire fighting is defined as either a fire fighting effort by the crew by use of water from the hoses and fire hydrant system on board if the ship is at sea or alternatively fire fighting efforts with help from the outside, e.g. a fire fighting vessel or the rescue service if the ship is in port or otherwise in proximity of land.

The NK (1994) report states that, out of 60 investigated machinery space fires, 12 fires were extinguished by sea water and another 3 fires were extinguished by the help of a fire fighting vessel, in total representing 25% of all fires. After disregarding the fires extinguished by means of portable extinguishers or the CO_2 system, both of which fire fighting efforts are assumed to take place before fully equipped fire fighters enter the machinery space, the percentage increases to 60%. This gives an indication that the success rate is fairly high to extinguish the fire this way. However since the report does not state any details of the fire fighting attempts for each individual incident it is difficult to use the data to come to any general conclusions.

According to an investigation into the effectiveness of CO_2 systems performed by Zalosh et al. (1996) the CO_2 often puts down the fire temporarily even though it does not always extinguish the fire completely. Out of the cases where the CO_2 system does not manage to extinguish the fire it temporarily extinguished the fire in 24% and controlled the fire in 12% of the fire incidents respectively. This indicates that release of the CO_2 system would still increase the probability of the following fire fighting attempt being successful. Since it is assumed that a CO_2 system is in place in 99% of all ships of interest (Busche 2009) it is also assumed that the CO_2 is generally released before fully equipped fire fighters enter the space.

It is believed that a fire fighting effort from the outside is usually the last resort to extinguish the fire, after manual fire extinguishing by portable means or alternatively the automatic fire safety systems such as sprinkler or CO_2 have failed. This approach results in a fair amount of time passing from the time of ignition until the fire fighting effort is initiated. However this also means that the fire is likely to have been affected and constrained although not extinguished. Therefore it is believed that the probability of fire fighters extinguishing the fire is rather high, and the expected probability is set to 80%. Given the uncertainties, an uncertainty interval of 25% is used in the calculations. It is believed that this probability is not much affected by the cause of the fire, because of the time assumed to have passed between the time of ignition and the initiation of the fire fighting effort. Hence the same distribution T(0.8 25/25) is used throughout the event tree, for scenarios /0,1/1/1,2/0/0/0/1/-/.

6.2 Personal Safety

The following sections describe the background information with respect to personal safety on each scenario and the assumptions on the consequence and probability distributions. Table E.3 gives all distributions used for each node in the event tree and the actual distributions for probabilities and costs are found in Tables E.4 and E.5.

6.2.1 Personal Injuries and Fatalities

Personal injuries and fatalities, where reported, have been assessed in the Thesis Database Search, and a similar assessment is presented in the USCG (1998) investigation. The consequences of fires with respect to personal safety from these two sources are summarised in Table 6.2.

Table 6.2: Data from the Thesis Database Search and the USCG (1998) report with respect to and personal injuries resulting from fire/explosion incidents.

	Thesis Database Search	USCG Report
Number of Incidents With Fatalities	2	9
Number of Fatalities	5	-
Percentage of Incidents With Fatality [%]	6.9	6.3
Number of Incidents With Personal Injuries	1	8
Number of Personal Injuries	1	-
Percentage of Incidents With Personal Injury [%]	3.4	5.6
Percentage of Incidents With Personal Injury/Fatality [%]	10.3	11.9

It is noted that personal safety is one of the key aspects when performing a risk analysis on fire/explosions, and according to the casualty data more than one in ten incidents result in personal injury or fatality. According to the Thesis Database Search a fatality occurs approximately twice as often as a personal injury. Based on the USCG (1998) investigation fatalities and injuries occur with roughly the same frequency. However, given the meagre selection of reported incidents and uncertainties when it comes to underreporting further statistical data has been taken into consideration in the risk analysis.

Fatalities tend, for obvious reasons, to be more widely noticed than minor or moderate injuries. However, apart from affecting the people involved injuries both provide an indication of high risk areas as well as induce further costs and are therefore taken into consideration within this risk analysis. To include both personal injuries and fatalities in the risk analysis and cost-benefit assessment a scale factor has been used to link the two categories. This methods allows for personal injuries to be taken into account when estimating the personal safety consequences of a fire/explosion incident, instead of only seeing to the number of fatalities. When analysing the risk control options this provides a helpful indication on the cost of personal safety in the cost-benefit assessment. Furthermore, calculating a total consequence for personal safety in combination with the *Willingness To Pay for a Statistical Life* allows for a financial estimation of the total safety cost.

To be able to relate the seriousness of a personal injury compared to the seriousness of a fatality the ratio between the two was set using various sources of statistical fire data. The data are summarised in Table 6.3.

Table 6.3: Ratio for fatalities and personal injuries for taking both kinds of casualties into account when estimating the personal safety consequences of a fire/explosion incident. (Harrami & McIntyre 2006, Hasofer & Thomas 2006, USFA & NFDC 2005)

Source	Ratio Fatality/Injury
Harrami and McIntyre	1/14
Hasofer and Thomas	1/10
US Fire Administration	1/5.2
Thesis Database Search	5/1
USCG Report	9/8

Harrami and McIntyre (2006) performed an investigation on *Fire and Fire Protection In Homes and Public Buildings* in Sweden from 2000 to 2004 on behalf of the Swedish Chemicals Inspectorate. The data include people killed where the fire was the determined cause of death according to the following (Harrami & McIntyre 2006):

- The victims shall have died due to a fire or explosive combustion process within a month of the incident.
- If a fire occurs as the result of a road accident then it must be clear that the victims. were living when flames or fire gases reached the body.
- People who are already dead as a result of trauma from road accidents, electricity, illness, hanging or other events are not included, even if the body afterwards was exposed to fire or an explosion.

Injuries were investigated according to the Swedish health authority's statistics and major injuries included people treated in a hospital for 24 hours or more due to one of the following reasons: building fire, non-building fire, ignition of clothing, ignition of flammable materials, other or unspecified fire or open smoke. Minor injuries were defined as injuries that call for acute treatment from the health authority but are not serious enough to require treatment as a hospital inpatient. It was noted that approximately 100 persons are killed in fires annually whereas 700 persons sustain minor and another 700 major injuries respectively. In conclusion this results in the number of injuries being 14 times higher than the number of fatalities. The majority of fires (79%) occurred in residential buildings, another 12% in public buildings and the remaining 9% in vehicles, the outdoors or other environments. Hence this data may differ from the maritime industry, but might still provide an indication of the ratio between the number of injured and dead.

Hasofer and Thomas (2006) analyses *Fatalities and Injuries In Building Fire Statistics* and note that only 9% of fires with casualties cause fatalities. The data is based on apartment fire statistics during 1993 from the *US National Fire Incident Reporting System (NFIRS).* The definition of fire fatality is not clearly stated, and furthermore the NFIRS data do not provide any details on the severity of the injuries reported. Therefore other health problems or injuries during escape may have affected the outcome and it can not be determined that all casualties are strictly caused by the fire itself.

The US Fire Administration (USFA & NFDC 2005) investigated 1.7 million fires, including 3300 fatal fires, in the United States in 2002 and concluded that 2.4 fatalities and 12.5 injuries occur per 1000 fires. Out of all fatal fires, similar to the Swedish investigation (Harrami & McIntyre 2006), approximately 70% occurred in residential structures, 20% in vehicles and the remaining 10% outside or in other places. The statistics is based on reports from local US fire departments and US state agencies through the NFIRS.

It can be noted that the fatality-injury fire statistics vary widely depending on the country and other circumstances. However, based on the above a fatality is considered equal to 10 average injuries for the purpose of this thesis. Though differing from the Thesis Database Search the fatality-injury ratio based on other fire data is considered more reliable given the large amount of data being the base of these investigations.

6.2.2 Consequences

The distinction between *minor* and *major* costs has been set as the occurrence of fatalities in the incident. A cost is consequently considered major if there has been one or more fatalities and minor if there are only personal injuries or alternatively no personal casualties at all. Throughout the thesis the cost unit used represent the number of *fatalities.* Hence if the expected cost is '1', one fatality is expected. A *personal injury* is defined as a case where the injury calls for medical attention of the person/-s involved, i.e. where a person requires either acute medical treatment or alternatively where the person seeks medical consultancy later. As further discussed in Section 6.2.1 an average moderate injury is considered equivalent to 0.1 fatalities.

Only two distributions have been used to describe all scenarios: minor and major costs respectively. Instead the probability distributions are varied depending on the likeliness of the various scenarios to differentiate the outcomes.

As mentioned above *minor costs* includes all outcomes with either no casualties or only injuries. Based on the definition of injury and fatality the consequence of a minor damage with respect to safety is always somewhere between 0 and 1. Since it is considered most likely that no one gets injured at all when a fire occurs, the most probable value is assumed to be 0. A Beta distribution was used for the costs, and adjusted as was considered reasonable with respect to statistical data on fire injuries, as presented in Table 6.2. This resulted in a minor cost distribution of $\beta(1, 50, 0, 1)$, with an average value of 0.02.

With respect to major damages it is believed that most deaths due to machinery space fire occur in the following cases:

- *An initial explosion* - If occurring when people are currently in the machinery space this could result in immediate injuries or deaths for people in the vicinity of the explosion.
- *Manual fire extinguishing with portable means* - A manual extinguishing effort is usually the first counter measure in case of a fire, before the crew is safely equipped with personal protection, resulting in a risk of smoke inhalation and/or burns.
- *Release of the CO_2 system* - There are strict routines on how and when the system should be released to ensure that no people are still in the machinery space, but should the routines fail the CO_2 constitute a great danger for anyone trapped in the space.
- *Fire fighting* - This is usually one of the last resorts when the fire has spread and constitutes great risks for smoke/heat injuries as well as possibly entrapment in the machinery space.

For major damages, i.e. fatalities, the minimum cost is 1 (based on the definition of major cost) and the maximum cost is 25, which represents the assumed number of crew on a larger oil tanker or container vessel. It is assumed that the vessels do not carry passengers. Since there is always a possibility, yet extremely unlikely, of an entire vessel sinking and the crew perishing. Since many of the somewhat smaller vessels have an even smaller number of crew the maximum cost consequence is considered even more unlikely, bringing the most probable cost much closer to 1. It is however considered reasonable that once a fatality occur the probability of another fatality is fairly high. This assumption is made based on the following reasons:

- Based on the statistical casualty data (see Table 6.2) a fatal incident does not seldom involve more than one death.
- Fire fighting is considered one of the greatest risks for personal safety, and a fire fighting effort usually involves more than one person. Hence, if something unexpected happens during the process more than one person is at risk.
- If a fire can not be extinguished by any of the fire safety systems or manually there is a risk of fire spread to the accommodation block and other parts of the ship, which would put all crew members at risk.

Based on the above the major cost probability used is a Beta distribution, $\beta(0.5, 25, 1, 25)$, resulting in an average cost of approximately 1.5 lives for each fatal incident.

6.2.3 Probabilities

Similar to previous scenarios the probability distributions have always been specified for the *minor cost* branches. The probability of a major damage is then defined as '1-P(Minor Cost)'.

Based on the high-risk events described in Section 6.2.2, i.e. apart from the fire itself an initial explosion, manual fire extinguishing by portable means, release of the CO_2 system and fire fighting, the probability of a minor damage was adjusted to suit. Each scenario was assessed on its total risk so that each of the high-risk events lowered the probability of a minor damage. The non-detected incidents were considered never to result in a major damage, since no person would be involved. Except for those scenarios an explosion that does not lead to a fire is considered the safest scenario, i.e. with the highest probability of a minor damage. Then the probability of a minor damage is gradually lowered depending on how many of the high-risk events that apply to the scenario.

Since there are no outcomes that specifically do not result in any casualties (those scenarios are included in the minor damage branch) it is considered that the probability of a minor damage is never below 75%. This assumption is based on both statistical casualty data as well as estimations on the likeliness of severe damages/fatalities in case of a machinery space fire and/or explosion. All probability distributions for minor damage are defined as Pert distributions with the minimum of 0.75 and the maximum of 1.0. The most probably value is derived as per the method described above, with a most probably value of 1.0 for the assumed most safe scenario (i.e. /1/0/-/-/-/-/-/1/), and then lowered by 0.02 for each high-risk event.

6.3 Financial Losses

The following sections describe the background information with respect to financial losses on each scenario and the main assumptions on the cost and probability distributions. Table E.3 gives all distributions used for each node in the event tree and the actual distributions for probabilities and costs are found in Tables E.4 and E.5.

6.3.1 Repair Costs Case Study

In order to estimate the financial losses following a fire Scandinavian Underwriters Agency (Munzel 2009) provided two reports covering repair costs after machinery space fires. A short description is given below.

Incident 1: Chemical tanker with a GT of approximately 11,000 built in 1992. The vessel suffered a fire that was located in the machinery space at the starboard side lower platform deck whereby mainly electrical equipment, the main engine, the purifier room, auxiliary equipment and the steel structure/tanks in the machinery space sustained severe thermal damages. Other equipment installed in the machinery space was severely affected by heat and smoke emissions.

Incident 2: Small dry cargo ship with a GT of approximately 3000 built in 2002. After activation of the fire alarm the Chief Engineer discovered a fire on the main engine. A leakage of the fuel oil delivery pipe between two cylinders was observed causing a spray of fuel oil on the engine's top. Immediate attempts to extinguish the fire failed and the engine room was evacuated, all ventilation stopped etc. to prepare for CO_2 flooding. After flooding the space twice with CO_2 the machinery space was entered by crew using breathing apparatus to extinguish the fire completely. Subsequent inspections revealed damages mainly to electrical equipment/cabling in way of the main fire area. Furthermore the entire machinery space was severely affected by heavy smoke emissions.

It is difficult to compare these two incidents and circumstances, or even to compare the costs of repair after fires on board ships due to the many factors involved, the features of the ship, the fire starting point and also how the fire propagates and the crew's behaviour. However these figures provides indications on the size of repair costs. With that in mind Table 6.4

shows the repair costs for the two incidents and Table 6.5 presents some estimations on prices to fit new machinery parts.

Table 6.4: Actual costs for repairing ships in the two cases provided by Munzel (2009). Prices heavily depend on many factors and should not be compared but can be used only as an indication of sizes. All costs are converted to 2008 Millions USD.

Type of Cost	Incident 1	Incident 2
Repairs and cleaning	3.37	0.52
Costs for owners	0.20	0.02
Part Total	3.57	0.54
Days in repair (laid off)	91	38
Estimated income loss	2.26	0.57
TOTAL	5.83	1.11

Table 6.5: Rough estimations on costs for machinery parts in USD based on Munzel (2009) and Vosvolis (2009).

Auxiliary engine/diesel generator	300,000
Boiler	120,000
Alternator	75,000
Blower	60,000
Turbocharger	150,000
Shaft generator	105,000
Oil pump	30,000
Starting air compressor	22,500
Entire main engine	1,500,000
Income loss per day*	15,000-50,000
Operation cost per day	up to 20,000

*Charter rates depend heavily on the world market and are considerably lower today (2009). The prices given are based on an estimate of normal market conditions over the last years.

6.3.2 Costs

The financial consequences of the incidents in the risk model have been classified as either minor or major damages. *Major damage* has been defined as total loss of the vessel, i.e. either sinking of the ship or if the fire damages are severe enough to constitute a constructive total ship loss. In the cases of constructive total loss the vessel is considered beyond repair to a cost less than the insurance value and scrapped (Munzel 2009). A *minor damage* is defined as any outcome being less severe than a total loss.

Total Loss

Since a *major damage* is considered equal to a total loss the new-building prices of oil tankers and container vessels have been used as guidance on the cost, and the financial loss is assumed equal to 60% of the new-building price. In these estimations other costs such as towing costs and income losses of the ship manager have not been taken into consideration. It is assumed that those costs are minor in comparison to the total cost of the ship. Furthermore while using the new-building price of vessels to represent the total loss of a ship it is believed that the values are overrated for the average ship, since it does not take the ship's age and current condition into account. Therefore, this over-valuation is considered to compensate for other damages in relation to the scrapping of a ship.

The new-building prices for all ships of interest, i.e. oil tankers and container vessels constructed 1998 or later, are found in the LRF Database (LRF 2009*a*). All amounts were re-calculated to values in 2008 US Dollars, as detailed further in Section 6.3.4. The new-building prices were then fitted to a distribution by using the @Risk software. After adjusting the minimum and maximum values to suit the extreme values in the data this resulted in a Beta distribution, β(2.37, 13.53, 5,000,000, 300,000,000). In the event tree calculations the values were defined as 60% of the values given by the distribution.

Minor Damages

Regardless of scenario the minor cost is always defined as the combination of income losses and actual repair costs. Further on the income loss in each case in defined as the expected charter day rate multiplied by the days the ship is expected to be laid up for repairs.

Based on estimations from Munzel (2009) and Vosvolis (2009) the ship charter rates are usually in the area of 5000 USD to 70,000 USD per day. These numbers are hugely dependent on the world financial market, but the day rates used in this report are believed to represent typical values at normal circumstances in the world market. Furthermore the values vary in relation to the ship size, the type of cargo, the route etc. and therefore a Pert distribution is used, in the interval of 5000 USD to 70,000 USD with a most likely value of 20,000 USD.

The repair time needed for after each scenario was determined with consideration to the expected severity of the fire, i.e. a fire that was extinguished early (e.g. by portable means) was assumed to require few days out of service whereas a longer-lasting fire was assumed to require several weeks out of service. However, since even minor fires can cause great damage with respect to smoke or water damage, extensive damage to electrical equipment etc. a fairly large time interval was used. Insurances usually covers repairs up to 180 days and, even though it is highly dependent on the circumstances, is is very unusual that a ship has to be taken out of service for longer periods than 6 months, according to Munzel (2009). As a guidance repair times for machinery space fires stated in the NK (1994) report were used, as presented in Table 6.6.

Fires that are never detected, /0,1/1/0/-/-/-/-/1/, are assumed only to cause very minor damages that are not required to be attended to straight away. Therefore those damages are assumed to be repaired as routine maintenance and will not require the ship to be taken out of service.

For fires that are extinguished manually by portable means, /0,1/1/1,2/0,1/0,1/-/-/1/, or with the help of a local sprinkler system, i.e. where the fire is contained to a small area and extinguished early it is believed that the damages are usually not very extensive. Therefore the time interval was set to between 0 to 30 days and a Beta distribution, $\beta(1.1, 15.5, 0, 30)$, was used, resulting in an average repair time of 2 days.

Table 6.6: Summary of repair times after machinery space fires as investigated in the NK report (1994).

Time (Days)	Number of Ships	Percentage (%)
0-14	21	38.9
15-28	10	18.5
29-42	9	16.7
43-56	7	13.0
57-70	4	7.4
71-84	1	1.9
85-98	1	1.9
99-105	1	1.9
$\overline{x} = 31.2$	$\sum 54$	$\sum 100$

All long-lasting fires, i.e. fires that are extinguished by the CO_2 system of by fire fighting, were treated in similar ways. It is assumed that the repair times vary between 0 to 180 days, and since release of the CO_2 system is considered to precede the fire fighting effort, it is assumed that fires extinguished by CO_2 are somewhat less severe, and therefore generally require shorter repair times. Based on the average repair times in the NK report (1994) this resulted in a beta distribution, $\beta(1.1, 5.5, 0, 180)$ being used for CO_2 extinguished fires, and a Pert distribution, Pert(0, 22.5, 180) being used for fires extinguished by fire fighting.

With respect to explosions without a following fire, /1/0/-/-/-/-/-/1/, the large uncertainties, both with respect to actual repair costs and repair times, resulted in a uniform cost distribution being used. Such incidents are believed to mainly involve the main engine or boiler, and could potentially result in the entire piece of machinery being destroyed, but could also involve significantly less damage. Furthermore the repair times are highly dependent on whether the mechanical repair work be carried out directly by the crew, or if the ship required attending to at a shipyard. Therefore a distribution U(10,000, 1,000,000) is used for this scenario.

The actual repair costs for each fire scenario have been estimated based on information on the two incidents discussed in Section 6.3.1. Since it is believed that the total repair cost is positively related to the repair time the repair cost is generally set as *cost per day multiplied by the repair time.* Due to uncertainties in the data all repair costs are given as uniform distributions. For smaller fires extinguished by portable means or the sprinkler system (/0,1/1/1,2/0,1/0,1/-/-/1/) the daily repair cost is set to U(2500, 2500), for fires extinguished by CO_2 (/0,1/1/1,2/0/0/1/-/1/) or fire fighting (/0,1/1/1,2/0/0/0/1/1/) U(5000, 50,000) is used. For fires that are not detected and considered not to require any particularly extensive repairs the main repair cost is considered to be replacement of certain machinery parts. This distribution is therefore set to U(0, 20,000). All costs above are given in USD.

6.3.3 Other Costs

Apart from the costs described above, being included as distributions in the risk model, there are a few financial costs that have not been specifically taken into account. These costs include insurance costs and towing costs and are mainly disregarded since they are mostly relevant in cases of total ship loss, where they are considered rather minor relative to the loss of the actual ship. Furthermore owner's deductibles and towing costs mainly affect a specific ship owner, whereas e.g. personal losses and workplace safety are matters involving the entire shipping industry.

Towing of a ship is mainly believed to influence the cost of a total ship loss, but may also be necessary after a smaller damage, e.g. if the fire has affected the propulsion machinery or the steering equipment. The cost is highly dependant on the circumstances regarding the incident, such as the location and condition of the ship, the value of the cargo and the time frame for transporting the ship to port. If the ship is drifting towards a coastline, threatens another vessel or constitute a danger for environmental pollution action has to be taken quickly, which increases the costs. Munzel (2009) estimates that such towing costs may amount to between 50,000 and several million USD, depending on the circumstances as discussed above.

With respect to insurance costs there are mainly three relevant parts: the annual insurance premium and the owner's deductibles as well as the insurance value of a ship. Though almost impossible to estimate in general terms, given the diversity of the world fleet with respect to age, condition, size etc. as well as the world market, Kay (2009) suggest that a typical container vessel of approximately 3500 TEU would have an annual insurance premium of around 100,000 USD. Though it is expected that all ships comply with current international safety requirements such as SOLAS, there are generally no discounts at all for any fire safety installations in addition to the standard regulations. The owner's deductibles again vary with the ship owner's fleet, external factors and the owner's risk awareness but may amount to approximately 50,000-100,000 USD for a container vessel of around 1500 TEU. (Kay 2009)

Whereas the insurance values of ships are discussed and in relation to the newbuilding prices of vessels and the financial cost of a total loss, other insurance costs and the towing costs are not described further in the risk model. These costs are however taken into account to a certain extent when discussing risk control options in Chapter 8.

6.3.4 Gross Domestic Product Index

Since the new-building price of all vessels in the Lloyd's Register Fairplay database is given as the contracted amount in USD at the time of construction all prices were re-calculated to the corresponding amount in USD of 2008 year's value.

The *Gross Domestic Product*, or GDP, is the market value of all goods and services produced in an economy for a certain period of time. Thus, by comparing the national GDP values for a country every year, a GDP deflator can be derived and used as a measure of inflation in the national market. (Baumol & Blinder 2006) Within this thesis it has been used as a price index that indicates the value of the US Dollar over the last 11 years. By dividing each amount with the appropriate index as per Table 6.7 all costs are given in the value of the 2008 US Dollar.

Table 6.7: US GDP index used to calculate the monetary value of amounts of USD from 1998 to 2007 to USD in 2008's value (BEA 2009).

Year	GDP Deflator Index
1998	0.788243
1999	0.799830
2000	0.817151
2001	0.835615
2002	0.849147
2003	0.867417
2004	0.892029
2005	0.921803
2006	0.951827
2007	1.021363
2008	1

6.3.5 Probabilities

The probabilities are always specified for a minor damage, and the probability of a major damage is therefore '1-P(Minor Cost)' for each scenario.

In the following cases the probability of a minor damage is considered to be 1, i.e. there is no risk of total loss:

- Where the fire is never detected (/0,1/1/0/-/-/-/-/1/). If the incident is small enough not to be noticed it can not cause a total loss of the ship.
- If the fire is successfully extinguished manually by portable means (/0,1/1/1,2/1/-/-/-/1/). Since a manual fire fighting effort is considered to be the first counter measure a fire that is extinguished quickly is assumed not to be able to release enough heat to affect the main steel structure. Hence, any damage will only be local.
- Similar to the above a fire that is extinguished by the sprinkler system (/0,1/1/1,2/0/1/-/-/1/)will be contained locally and will not damage the steel construction to any great extent, based on the assumption that the ships of interest only have local sprinkler applications by the high-risk components, and not full coverage systems.
- If the initiating event is an explosion, and not followed by a fire (/1/0/-/-/-/-/-/1/) it is not assumed possible to result in a total loss.

On the contrary to the above a major damage is considered to be the only possible outcome if a fire can not be extinguished at all, i.e. if the last fire fighting effort fails to put out the fire. A fire that can not be extinguished constitute a great risk of releasing large amounts of heat that causes collapse of the load-bearing structure of the ship. Even if the ship does not sink it is considered very likely that it has to be scrapped due to its condition and the huge repair costs.

In the four remaining scenarios the probability of a minor cost is based on the fire fighting media, i.e. CO_2 or fire fighting, and whether the fire is preceded by an explosion or not. All distributions are defined as Pert distributions in the interval between 0.75 and 1. Based on the assumption that most fires do not cause major damages to the ship (see Chapter 5 for further information) together with the choice of distribution this is considered to be a reasonable estimate.

The case of a fire not initiated by an explosion, that is extinguished by means of the CO_2 system is believed to be the least severe of the remaining scenarios and is therefore described by Pert(0.75, 1, 1) (/0/1/1,2/0/0/1/-/1/). The same scenario but where the initiating event is an explosion is given a similar distribution but with the most probable value being slightly lower, Pert(0.75, 0.98, 1) (/1/1/1,2/0/0/1/-/1/). If the fire is not preceded by an explosion but extinguished and slightly longer-lasting, i.e. extinguished by fire fighting rather than the CO_2 system the probability of a minor damage is assumed to be Pert(0.75, 0.96, 1) (/0/1/1,2/0/0/0/1/1/). Finally a fire that is initiated by an explosion and not extinguished until the fire fighting succeeds is given a probability distribution of Pert(0.75, 0.94, 1) (/1/1/1,2/0/0/0/1/1/).

7 Results

Results from the hazard analysis, risk model simulations with respect to incident frequencies, probabilities and costs are described in the sections below. This is followed by a sensitivity analysis in Section 7.3.

7.1 Main Hazards

It was shown that generators and leaking fuel pumps were the most critical components with respect to fires whereas boilers initiated the most explosions. In general electrical failures (usually originating from the generators or switchboards) and fuel leakages in pumps, piping and the main combustion machinery (the generators and the main engine) were the most common sources of fire.

7.2 Simulation Results

The following sections describe the results of the risk model simulations. The most important results are presented in Table 7.1. More detailed values of probabilities and cost intervals are presented in Table F.1. Further discussions of the significance of the consequences can be found in Chapter 9.

Table 7.1: Results from the risk model simulations with a 90% confidence interval. Values are presented both per shipyear and per year for the entire world fleet of oil tankers (2526 ships) and container vessels (2520 ships) constructed 1998 or later.

Result	Mean	Percentil		Unit	
		5%	95%		
Frequency	2.51	1.58	3.84	$\times 10^{-3}$	incidents/shipyear
	12.64	7.98	19.38		incidents/year
Safety	3.02	1.23	6.35	$\times 10^{-4}$	lives/shipyear
	1.52	0.62	3.21		lives/year
Financial	11.51	3.86	24.25	$\times 10^{3}$	USD/shipyear
	58.10	19.48	122.38	$\times 10^{6}$	USD/year

7.2.1 Frequency of Fire and/or Explosion

Based on the input data defined in Chapter 5 (i.e. data from the Thesis Database Search, the NK (1994) report and the OREDA (2002) handbook) the expected frequency for fire or explosion in the machinery space amounts to 2.5×10^-3 incidents per shipyear, with a $\mathrm{CI}_{90\%}(1.6 - 3.9) \times 10^{-3}$ (see Figure 7.1).

The probability of an oil tanker or container vessel suffering a fire/explosion during a certain period of time is calculated by use of Equation 7.1, where t is the time in shipyears and λ is the incident frequency per shipyear.

$$P(t) = 1 - e^{-\lambda t} \tag{7.1}$$

By using Equation 7.1 the expected probability of a fire/explosion during a shipyear is calculated to 0.0025 ($\mathrm{CI}_{90\%}$ (0.0016-0.0038)). During a ship's lifetime (which is assumed to be 25 years as per the discussion in Section 3.1) this results in a probability of 0.061 ($\mathrm{CI}_{90\%}$ (0.039-0.092)).

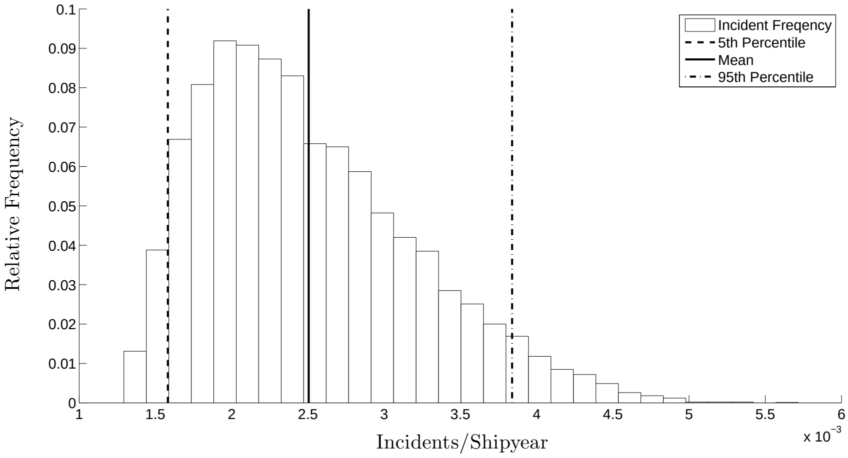


Figure 7.1: Distribution for the incident frequency rate, mean 0.0025 $CI_{90\%}$(0.0015-0.0038) incidents/shipyear.

For the entire world fleet of 2526 oil tankers and 2520 container vessels built 1998 or later (which is about 40% of the total fleet of oil tankers and container vessels) (LRF 2009*b*) the expected frequency of fires and/or explosions is 12.6 incidents annually.

7.2.2 Personal Safety

Losses with respect to personal safety are divided in fatal incidents (major costs) and personal injuries (minor costs). This section mainly describe losses in human fatalities/injuries. Although almost impossible to quantify, a discussion on the financial equivalence of life is found in Section 8.1, resulting in a *value of a statistical life* of 6 Million USD being used in the cost-benefit analysis.

The expected probability of one or more fatalities, given that a fire/explosion has occurred, is 0.070 ($\mathrm{CI}_{90\%}$ (0.042-0.100)). This results in an expected total personal safety loss of 0.12 lives ($\mathrm{CI}_{90\%}$ (0.060-0.227)) for each fatal incident.

Assuming an incident frequency as stated above the expected frequency of fatal accidents amounts to 1.8×10^{-4} ($\mathrm{CI}_{90\%}(0.86 - 3.0)\ \times 10^{-4}$) per shipyear. Alternatively, as per Equation 7.1, the probability of a fatal accident during a shipyear is 0.00018 ($\mathrm{CI}_{90\%}$ (0.000086-0.0003)). The probability of a fatal accident during a ship's lifetime amounts to 0.0044 ($\mathrm{CI}_{90\%}$ (0.0021-0.0134)).

The total loss with respect to personal safety is expected to amount to the loss of 0.00030 lives ($CI_{90\%}$ (0.00012-0.00064)) per shipyear (see Figure 7.2), which results in a loss of 0.0075 lives ($CI_{90\%}$ (0.0031-0.0159)) per ship lifetime.

For the entire world fleet of oil tankers and container vessels built 1998 or later a loss of 1.5 lives is expected per year.

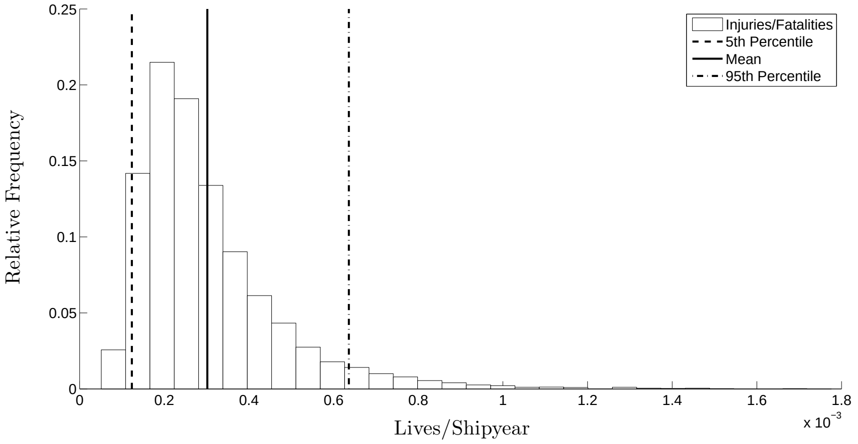


Figure 7.2: Distribution for injuries/fatalities, mean 0.00030 $CI_{90\%}$ (0.00012-0.00064) lives/shipyear.

7.2.3 Financial Losses

For financial losses a distinction was made between total ship loss (major cost) and other damage (minor cost). 12% of the incidents result in a total loss (i.e. either sinking of a ship or a constructive total loss), with a $CI_{90\%}$ (5.9%-18%), each total loss resulting in a financial loss of 29 Million USD, with a $CI_{90\%}(9 - 59)$ Million USD.

Most fire/explosion incidents, 88% with a $CI_{90\%}$ (82%-94%), result in minor damages (i.e. not total loss), but can induce fairly large costs in the form of repair costs and income losses. The costs are defined differently depending on how long the fire is allowed to propagate and the extent of damages expected from the fire extinguishing medium, and range from 10,000 USD ($CI_{90\%}(1000-20,000)$ USD) for a manually extinguished fire by portable means to 2.4 Million USD ($CI_{90\%}(300,000-6,000,000)$ USD) for a fire that is extinguished by fire fighters. Given a minor incident the expected cost amounts to 300,000 USD ($CI_{90\%}(1,000,000-2,000,000)$ USD).

Given the fire/explosion frequency as presented in Section 7.2.1 the total expected financial loss per shipyear has been calculated. This results in an expected loss of 12,000 USD ($CI_{90\%}(4000 - 25,000)$ USD) (see Figure 7.3) from fires/explosions in the machinery space per shipyear. Assuming a lifetime of an oil tanker or container vessel of approximately 25 years (see Section 3.1) the total expected financial loss of machinery space fires amounts to 300,000 USD ($CI_{90\%}(100,000 - 600,000)$ USD).

By the use of Equation 7.1 the expected probability of a total loss (i.e. sinking or a constructive total loss) is 0.0003 ($CI_{90\%}$ (0.00013-0.00054)) during a shipyear. During the lifetime of a ship the probability of a total loss amounts to 0.0075 ($CI_{90\%}$ (0.0032-0.0134)).

For the entire world fleet of oil tankers and container vessels built 1998 or later (LRF 2009*b*) a total loss of about 58 Million USD is expected per year.

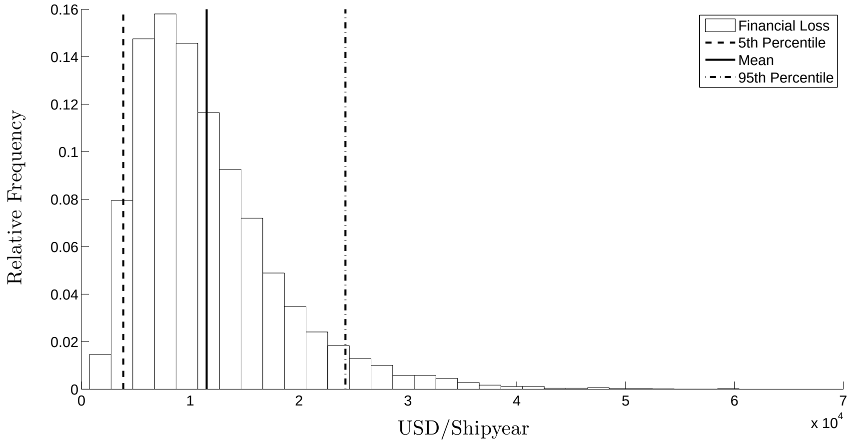


Figure 7.3: Distribution for financial loss, mean 11,510 $CI_{90\%}$ (3860-24,250) USD/shipyear.

7.3 Sensitivity Analysis

Since most risk model variables are not defined as specific values but as distributions, and can therefore vary widely, it is essential to investigate the sensitivity of the final result with respect to the different variables. As discussed earlier in Chapters 5 and 6 there are uncertainties in the input data due to insufficient information in the statistical data and difficulties in generalising and predicting the course of a fire scenario. Given these large uncertainties it is considered important to identify the most critical input variables, and the following sections contain discussions on the sensitivity of the data. The correlations between the variables and the output has been calculated by @Risk based on the risk model simulations. Input variables that show very little correlation to the output have been disregarded, and only the five variables with the highest correlation to the result are shown in the Figures 7.4 to 7.7.

7.3.1 Incident Frequency

As shown in Figure 7.4 the incident frequency is most sensitive and positively correlated to the OREDA input data, i.e. the *hot surface* factor, *critical leakage* factor, *other ignition* factor as well as the number of pumps and valves. As indicated in Figure 7.4 the other two main data sources, i.e. the *Thesis Database Search frequency* and the *NK frequency* have a smaller influence on the final incident frequency. The NK frequency shows only very little correlation (0.02) whereas the Thesis Database Search and the incident frequency have a slightly higher but still very low correlation of 0.06.

Given that the calculated OREDA frequency is considerably higher than those from the other sources it is not surprising that its input data show a bigger influence on the result. However it is noted that the incident frequency is highly correlated to the estimated factors, *hot surface* (0.73) and *critical leakage* (0.60) in particular. Whereas the *other ignition* factor (0.17) and the numbers of pumps (0.16) and valves (0.13) are all based on statistical data the other factors are mostly rough estimations on the amount of machinery and piping hot enough to ignite a fuel spill, and an assumption on how many of leaks can cause enough fuel to disperse for it to start a fire. Due to the uncertainty in the assumptions the factors are defined as uniform distributions with a ±50% and ±60% interval respectively. Therefore, even though they are highly correlated to the final incident frequency, the uncertainty has been accounted for and the factors are considered reasonably estimated to the extent possible based on the available data.

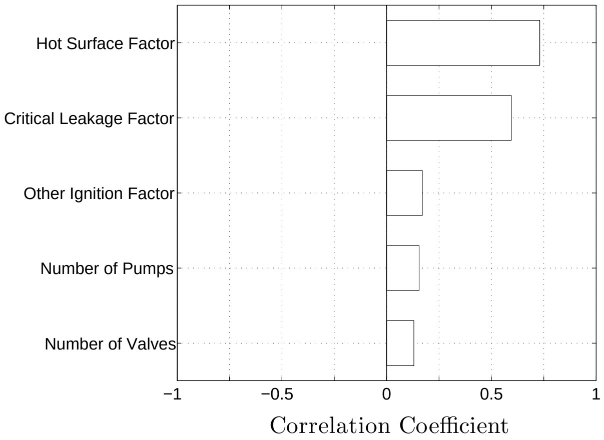


Figure 7.4: Tornado diagram for incident frequency rate, showing correlation for input variables.

7.3.2 Personal Safety

The correlations of input variables with respect to the probability of a fatal incident are shown in Figure 7.5. The correlations indicate that the probabilities of a minor damage (i.e. non-fatal incident) are the by far most highly correlated variables. The five most correlated minor damage probabilities involve: fires extinguished by fire fighting (-0.7), fires extinguished by portable means (-0.5), fires extinguished by the CO_2 system (-0.4), fires that lead to a total loss of the ship (-0.2) and finally an explosion with following fire that is extinguished by fire fighting. Since a higher probability of a minor damage automatically means a lower risk of a fatal accident it is reasonable to assume that all variables above should be negatively correlated to the total loss, which is also seen in Figure 7.5.

Figure 7.6 shows the correlations with respect to total personal losses per shipyear. As expected it is concluded that the *major cost*, i.e. the personal loss in case of a fatal accident is the variable correlating most with the total cost (0.5). In a similar way, the *minor cost*, i.e. the personal injuries following a fire/explosion incident, is correlated to the result (0.3). It is considered logical that the personal loss (cost) in each scenario has a big influence on the expected total personal loss per shipyear. Since the cost following a fatal accident (i.e. deaths) are always more severe than that of a non-fatal accident, it is expected that the major cost is more influential on the final result.

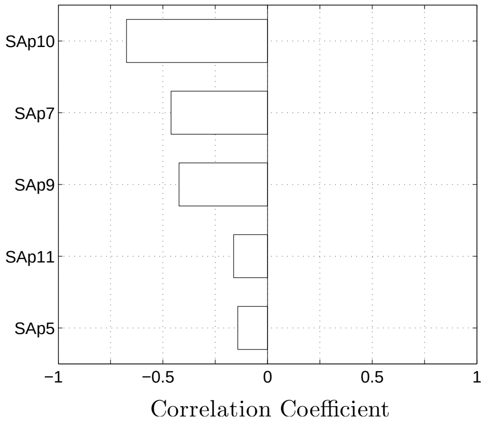


Figure 7.5: Tornado diagram for probability of fatalities given incident, showing correlation for input variables (SA_p10 probability of a minor damage if the fire is not initiated by an explosion and extinguished by fire fighting, SA_p7 probability of a minor damage if the fire is not initiated by an explosion and is extinguished by portable means, SA_p9 probability of a minor damage if the fire is not initiated by an explosion and is extinguished by the CO_2 system, SA_p11 probability (=0) of a minor damage in case of a total loss if the fire is not initiated by an explosion, SA_p5 probability of a minor damage if the fire is preceded by an explosion and extinguished by the sprinkler system).

Apart from the actual cost distributions the OREDA input data *hot surface factor* (0.4) and *critical leakage factor* (0.3) show a fairly high positive correlation with the total cost. The *other ignition factor* (0.1) is also slightly correlated to the total outcome. Since all three factors proved important when deciding the expected frequency of incidents it is reasonable to assume that they would influence the expected total personal loss as well. This shows however, as discussed above in Section 7.3.1, that the estimated factors are highly influential to the final result.

The actual probability of a total loss is of course an important factor, which is shown by the negative correlation of the probability of a *minor damage* if the fire is extinguished by fire fighting (-0.3), CO_2 extinguishing system (-0.2) and portable extinguishing (-0.2) to the total cost. All the variables mentioned relate to fire incidents without an initiating explosion. This is believed reasonable given that these scenarios represent more than 80% of the cases, and hence the properties of these scenarios are more important for the final result. The fact that the probabilities are negatively correlated to the total personal loss simply indicates that the danger for human casualties is correlated to the *minor damage* probabilities, which is not very surprising given the way the risk model is constructed.

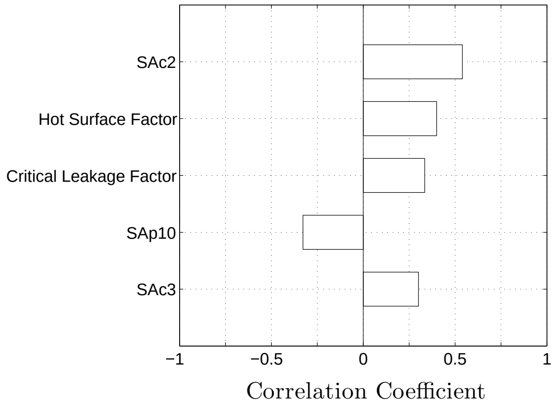


Figure 7.6: Tornado diagram for injuries/fatalities, showing correlation for input variables (SA_c2 Personal loss of a fatal incident, SA_p10 Probability of a minor damage if the fire not initiated by an explosion and is extinguished by fire fighting, SA_c3 Personal loss of a minor (non-fatal) incident).

7.3.3 Financial Losses

The Tornado diagram showing the correlations to the probability of a total loss (i.e. sinking or a constructive total loss) is shown in Figure 7.7. It is concluded that the probability of succeeding with a fire fighting effort is the single most correlating variable (-0.9), which is assumed reasonable with consideration to fire fighting being the last resort in extinguishing the fire. Other factors affecting the probability of a total loss are the probability of a minor damage if the fire is extinguished by fire fighting (-0.3) and similar but for the CO_2 system (-0.2). This is followed by the probability of the CO_2 system being successful (-0.1) as well as the probability of succeeding to extinguishing the fire by portable means in case of early detection (-0.1). All the above is rather logical, considering that the distinction between a minor or major cost results in very different cost distributions. Hence, the probability of a minor cost is expected to be an important variable.

Figure 7.8 shows the correlations with respect to the total financial losses per shipyear, with the cost of a total loss being the single highest correlated variable (0.7). Given that this ship value is defined as one distribution regardless of the scenario leading up to the ship loss, in combination with the amount being very large, this is not very surprising. Since the total cost is very dependent on the expected frequency of a fire/explosion incident the input into those frequency calculations will be of major importance for the cost. Hence, as shown in Figure 7.8, it can be established that the OREDA input data *hot surface factor* (0.3) and *critical leakage factor* (0.3) also influence the total financial loss cost.

The other two factors influencing the final result the most are the probability of a successful fire fighting effort (-0.3) and the repair time (i.e. the number of days the ship has to be taken out of service) if the fire is extinguished by fire fighting (0.2). The later is crucial for determining both the actual repair cost (since the total repair costs are defined as a certain daily sum in the risk model) and the income losses, and in combination with the repair time assumed to be rather long (see Table E.3) for a ship suffering from a fire that was extinguished

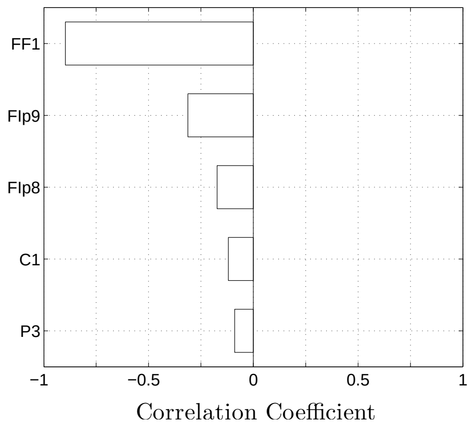


Figure 7.7: Tornado diagram for probability of total loss given incident, showing correlation for input variables (FF1 probability of successful fire fighting, FI_p9 probability of a minor damage if the fire is not initiated by an explosion and is extinguished by fire fighting, FI_p8 probability of a minor damage if the fire is preceded by an explosion and extinguished by fire fighting, C1 probability for CO_2 system extinguishing a fire, P3 probability for portable extinguishing in case of no explosion and early detection).

by a fire fighting effort, the total cost will be very sensitive to the repair time.

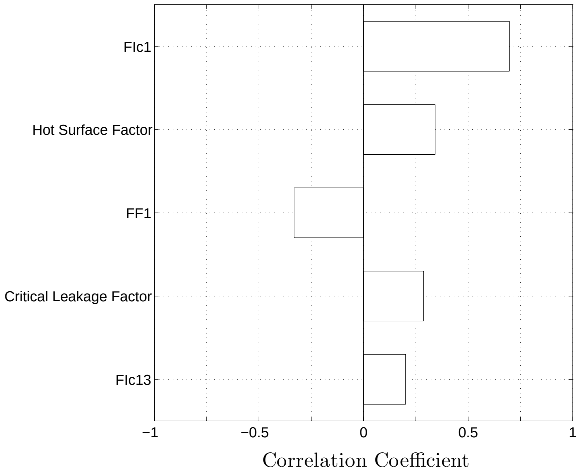


Figure 7.8: Tornado diagram for financial loss, showing correlation for input variables (FI_c1 *cost of a total loss based on ship value, FF1 probability of successful fire fighting,* FI_c13 *days laid off for repairs in case where a fire is extinguished by fire fighting).*

7.3.4 Summary

The results presented in the sections above indicate that the variables most correlated to the costs are generally the ones initially expected to have a big influence on the results, e.g. the expected financial cost of a total ship loss, and the expected personal loss in case of a fatal accident. Since all scenarios result in either a minor or major damage, and that all major damages are defined with the same distribution (one for financial loss and one for personal safety), those distributions are bound to largely affect the total expected cost. Furthermore the probabilities of different fire extinguishing systems, and the probability of actually completely extinguishing the fire at all, are naturally of great importance.

However there are factors believed to affect the final result to a great extent, but that were not shown to be among the most critical variables in the sensitivity analysis. For example the relation between the CO_2 system and human casualties is rather interesting. On one hand there is always a risk in releasing a CO_2 system, should there be people trapped in the space, but on the other hand a successful CO_2 system prevents the fire from spreading beyond the machinery space, as well as reducing the risk for the crew in connection with a following fire fighting effort.

Furthermore, given the way that the risk model is constructed the expected repair time (i.e. the time the ship has to be taken out of service) is believed to be a significant factor for determining the total cost with respect to financial losses. This is mainly due to the fact that the repair time is a factor both when calculating the actual repair costs, but also more importantly when calculating the income losses. It is therefore somewhat surprising that the correlations between repair times and expected costs of fires/explosions are not greater, and as per the simulations are only highly relevant with respect to fires extinguished by fire fighting efforts.

In summary the simulations show that the costs for major damages (i.e. financial total losses or fatalities) are the most significant, along with the probabilities of extinguishing fires (which in turn to a great extent determine the probability of a major damage), for deciding the expected cost of an incident, whereas the OREDA data and estimations prove important for calculating the frequency of fires/explosions occurring.

8 Risk Control Options

Although finding and evaluating proper risk control options has not been the main focus of this thesis this chapter provides some examples on some means to reduce the risks and impact of fires and explosions in machinery spaces.

In order to see how much is reasonable to pay for a reducing counter measure a comparison on the expected loss as it is today with the measure implemented is done. Since the losses are not only measured in monetary terms, such as property loss or loss of income due to reparations, but also as injuries or fatalities a discussion on the willingness to pay to avoid an injury or fatality in money is put first in this chapter.

After this two examples on how to reduce risks are presented, and using the model developed a calculation is made on how much these counter measures are worth, i.e. the willingness to pay for the implementation.

8.1 The Value of a Statistical Life

The comparison between financial losses and personal fatalities and injuries is a difficult subject. Human life is of course invaluable and it is impossible to put a financial estimate on the loss of a life. When it comes to risk analyses it is however useful to be able to estimate people's willingness to pay to avert a fatality. After all, in reality there are practical limitations to the resources available to introduce certain safety measures.

The FSA guidelines (MSC 2007*a*, Appendix 7) provide examples on how to calculate indices for cost effectiveness. There values for NCAF and GCAF (Net Cost of Averting a Fatality and Gross Cost of Averting a Fatality) are given to 3,000,000 USD. However this value is quite old and should be updated annually, further more it has been hard to find out how these values were calculated.

Therefore, in order to make an overall cost-benefit assessment of the risks and expected costs and to relate the consequences in the form of financial losses with human losses it is essential to estimate an up-to-date *value of a statistical life* (VSL). Various studies have been made on the subject, usually one of the following three types of studies (Leggett, Neumann & Penumalli 2001):

- *Wage-Risk (WR)* - An investigation of worker's wages in relation to the level of risk involved in the job.
- *Contingent Valuation (CV)* - People are asked about how much they are willing to pay for various risk reducing measures.
- *Consumer Market Analysis (CM)* - Consumers' *willingness to pay* (WTP) for risk reducing measures is investigated by analysing market trends and consumption.

Leggett et al. (2001) have collected information from various studies on VSL, and conclude that the results vary widely between different studies. This is partly explained by differences in the types of studies. Contingent valuation studies are for example sensitive to the welfare of the people taking part in the study, i.e. the mean income has proven to affect the willingness to pay positively. Altruism is also believed to influence people to state a higher value of the WTP than they would actually pay in reality. For a wage-risk analysis to prove a fair method it is essential that the risks are well documented, and that the workers are fully aware of the risks. Furthermore countries where workers' rights are well looked after are more likely to pay their workers more for high-risk jobs. In general the type and state of the economy in the country where the study is performed will always influence the results. (Golan & Kuchler 1999)

Table 8.1 depict the results from seven studies on VSL performed between 1989 and 2001, as presented in Leggett et al. (2001). All values were given in 2001 USD and have been calculated to 2008 USD as per the method described in Section 6.3.4.

Table 8.1: Summary of studies on VSL, the types of study and recommended values according to the authors of each study. The data is collected from Leggett et al. (2001).

Study	Type of Review	Types of Studies Included	Recommended VSL [Million USD 2008]
Fisher et Al (1989)	Narrative	WR ,CV, CM	9.69
Miller (1990)	Narrative	WR, CV, CM	3.95
Viscusi (1993)	Narrative	WR, CV, CM	8.02
Desvousges et Al (1995)	Meta-Analysis	WR	4.91
Miller (2000)	Meta-Analysis	WR, CV, CM	5.15
Kochi et Al (2001)	Empirical Baynesian Meta-Analysis	WR, CV	7.66
Mrozek & Taylor (2001)	Meta-Analysis	WR	2.51
Average			5.98

Given that the VSL presented in Table 8.1 represent all three types of studies (i.e. wage-risk, contingent valuation and consumer market), and that the studies different have been performed over a 12 year period it is believed that the values are fairly representative of what society in general is willing to pay for a risk reduction that saves one statistical life.

Based on the above a value of 6 Million USD is assumed reasonable to use as the VSL for the cost-benefit analysis within this thesis. It is difficult to translate this number into a value for each personal injury, given that there are many factors affecting the severity of a injury, both with respect to medical costs and non-economical factors. However, for this thesis it is assumed that an average injury is equivalent to 0.1 fatality. This assumption is based on the expected ratio of injuries compared to fatalities as discussed in Section 6.2.1 and the expectation that people are willing to pay significantly more when a life is at stake, resulting in the main factor affecting the cost of an injury being the actual cost of the medical treatment.

8.2 Human Error

Although it has not been possible (within the frame of this thesis) to determine the root cause for the incidents leading to explosion and/or fire in machinery space other papers give strong indications that human error is big contributing factor. It is hard to give a good picture on human errors leading to fires and therefore a more general discussion on human errors follows.

Eleye-Datubo, Wall & Wang (2008) conclude that studies show that equipment, mechanical, and structural failure together are far outstripped by human errors as the sole or major cause of incidents giving rise to claims. According to The Nautical Institute (2003) the human error cost the maritime industry 541,000,000 USD a year, and furthermore it is concluded that 62% of all major claims are directly attributable to error by one or more individuals. Tangen (1987) shows similar results and estimated that 60% of all causes of shipping accidents were due to human error. Further 15% were due to procedural or administrative errors and 25% to technical errors.

Human errors include (HSE 2001):

- Slips - making an unintended action through lack of attention or skill.
- Lapses - unintended actions due to memory failure.
- Mistakes - an intended but incorrect action.
- Violations - a deliberate deviation from standard practise.

To reduce human error is often among the most cost-effective ways of reducing risk, but on the other hand it is hard to estimate how the impact will be. It is difficult to know exactly how people may contribute to accidents and how they act in response to or escape from any accidents that do occur. Since an analysis of these factors is outside the scope of this thesis interested readers can read more on how to estimate these factors in HSE (2001) (i.e. Human Factor Assessments, Human Reliability Analysis, and Safety Management Systems).

8.2.1 Cost-Benefit

As discussed above there is a lot of potential loss to be saved if the risk awareness is increased throughout an organisation. This can be done in many ways, such as education personnel that work in the machinery space on a continuous basis or implementing policies to spread *lessons learnt* within the company.

The USCG (1998) report provides close to 30 recommendations on how to reduce the frequency or effects of fuel oil/lube oil spray fires on board vessels. Many of these involve new technical barriers to be implemented but often in combination with a new procedure to address the fact that it is often a slip or mistake made by a person that is the triggering factor. Their report includes 11 recommendations on management practise to help reduce the risks and/or impact.

The recommendation in the USCG (1998) report are somewhat outdated and some even already standard practise. But there is always room for improvement in this area, especially since the there might be companies that neglect safety and/or care less about these issues.

If assuming a new policy would reduce the frequency of fires in machinery space with 25% our model shows that the expected financial loss per ship life (assuming a ship life of 25 years) would be in $\mathrm{CI}_{90\%}(60-150)$ $\times 10^3$ USD. If including the willingness to pay for loss of life (see Section 8.1) the potential saving is even greater $\mathrm{CI}_{90\%}(80-170)$ $\times 10^3$ USD. Given that a new policy like this would not only affect one ship but a whole fleet there is a lot of money to save over time. Furthermore implements like these would also affect or could be easily adapted for a small cost to include other risks (e.g navigational, loading/unloading cargo etc.).

8.3 Alternative Fire Suppression Systems

Since the ban on Halon fire suppressing systems various systems have been refined and developed to match the large benefits that came with the use of the highly environmental unfriendly Halon. The use of normal sprinkler systems on board on ships is mandatory in the accommodation areas (FSS Code 2007), for usage in machinery spaces it has however so far been regarded as unsuitable although other suppression systems than CO_2 are allowed. It is estimated that 99% of all ships use the CO_2 systems for the machinery space (Busche 2009). The main problem with using CO_2 is that it is toxic for humans and that time consuming efforts, such as closing ventilation flaps and making sure that no one is left in the machinery space before it can be used, result in a delay in releasing the gas, which gives the fire more time to grow.

The general regulations regarding fire protection systems in machinery spaces are described in SOLAS (2009) and the FSS Code (2007) (see Section 2.2). The ways of seeing if a certain suppressing method achieves the required standards is to consult the *Revised Guidelines For the Approval of Equivalent Water-Based Fire-Extinguishing Systems For Machinery Spaces and Cargo Pump-Rooms* (MSC 2005) which provides detailed information on how the test fires should be set up and what kind of fires must be extinguished by the system tested. It divides the machinery spaces in three classes; I ($<$500 m^3) II (500 m^3 - 3000 m^3) and III ($>$3000 m^3) The IMO sub-committee for Fire Protection (FP) is currently preparing an additional standard for larger machinery spaces, and there are indications that it may be on the basis of a zone oriented approach.

Rushbrook (1998) believes that water based systems are good alternatives to use, even though many are afraid of the damage done by the water. By using water based systems there is free supply of water and that it can be released quickly (i.e. without evacuation) and the total damage on the machinery due to the water would be smaller than if the fire is allowed to grow during the time it takes to release the CO_2 system. Furthermore a water based system could be set of locally in sectors where needed, minimising damage done by water.

Below are two possible alternatives to use in machinery spaces on board ships.

8.3.1 Water Mist

Water mist systems use normal water that is released under high pressure and through special nozzles which distribute the water in really small droplets that have a large surface area and can therefore effectively lower the temperature of the flames and suppress a fire effectively. Also the small droplets mean that it behaves more like a gas and therefore can reach places where conventional sprinklers are insufficient.

In the literature studied, test results are presented for water mist suppression in compartments ranging from 6 m^3 to 3000 m^3, both for test-rooms and real engine rooms. It is shown that water mist can be an effective medium to extinguish Class B fires[2]. Results indicate however that these systems would have trouble extinguishing all fires in Class III engine rooms (Bill, Hansen & Richards 1997, Bill, Carlebois & Waters 1998, NLR 1999).

In addition to using just water mist there are different approaches to use additives in the water such as Aqueous Film Forming Foam (AFFF). SINTEF (2006) made 17 tests and

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[2] A = Wood, paper, cloth, trash and other ordinary materials. B = Gasoline, oil, paint and other flammable liquids

concluded that only one did not comply with the requirements in the given IMO testing protocol mentioned above (i.e (MSC 2005)).

The main advantage over CO_2 systems is that water mist is non-toxic and even if it the system does not manage to put out the fire it dramatically lowers the temperature in the flames so that fire fighters can enter and the space and extinguish the fire by other means. Furthermore the compartment does not have to be sealed before release due to the continuity of water supply, although it is more effective when sealed off. In the case of CO_2 systems the compartment has to be closed off before deployment of the gas, since there is a limited amount of gas on board (Burch 2006).

Some of the reports show that test fires were put out in matter of seconds or minutes. But these results would not be reliable according to the main conclusion made by Arvidson & Hertzberg (2003), suggesting that the time to extinguishing is not a very repeatable variable. Some of their tests were repeated under the same conditions and indicated a 20% to 80% difference in time.

There are various findings with respect to water mist fire suppressing systems in the machinery space, many of which are too detailed for this thesis and interested readers are referred to the above stated references. Furthermore there are also other water based systems such as high pressure water spray systems and these are, if mixed with foam, also very attractive alternatives to use in machinery spaces (Rushbrook 1998).

8.3.2 Aerosol Extinguishing Systems

Aerosol agents are a type of fire extinguishing chemicals that are discharged as solid particles, typically less then 10 micron (10^{-6} m) in diameter. When the particles hit a flame they will react with the fire radicals produced during combustion resulting in extinguishing of the fire. Similar to the water mist the particles provide a large surface area for, in this case, capturing the radicals and making them effective extinguishing agents. The following information is taken from Back, Boosinger, Forssell, Beene, Weaver & Nash (2009).

A total of 18 test were conducted using systems from three Aerosol Extinguishing Systems (AES) manufacturers. All systems were tested against the current IMO test protocol for approving AES in machinery spaces. The aerosol is discharged as a hot white smoke that reduces the visibility to about 0.3 m (assuming an illuminated source) and increases the temperature up to 25°C above ambient. The generator that releases the aerosol typically reaches hundreds of degrees Celsius, requiring a safe storage away from combustible materials.

With respect to the extinguishing capabilities of the systems tested all of them showed good capabilities against Class B fires but only 1 fire out of 14 Class A fires was extinguished. Furthermore the amount of carbon monoxide generated by the systems poses a potential health risk for personnel in the space. As a result none of the systems met the IMO requirements successfully. But some recommendations to the manufacturers as well as for the IMO test fire scenarios were made so that the system could be developed further and maybe be used in the machinery space on board ships in the future.

8.3.3 Cost-Benefit

If assuming that the CO_2 system would be replaced by a water sprinkler system with the same reliability described in Section 6.1.5 (i.e. 17% to 64%) the risk model shows that it would lower the expected losses by $\mathrm{CI}_{90\%}(1000-2400)$ USD per shipyear, compared to the present state. A change like this would give effect throughout the entire time a ship is in operation (on average 25 years, as per Section 3.1) and it is then more suitable to calculate it over a shipyear which yields $\mathrm{CI}_{90\%}(28,000-69,000)$ USD per shiplife. (this value includes economic equivalence to personnel injuries/fatalities, although quite small in the context, see Section 8.1).

This shows that one would be willing to pay $\mathrm{CI}_{90\%}(28,000-69,000)$ USD for installing a sprinkler system to cover the whole machinery space for it to be cost effective. The costs of maintaining is not taken into account since it is believed to be approximately the same as for the CO_2 system that it replaces. The general cost of the installation is not possible to give as it depends on several factors such as the volume and height of the machinery space. However (af Schmidt 2009) estimates that the installation of a full sprinkler system would cost approximately 45% more to install than a CO_2 system. Engel (2009) provides a value for high pressure water mist systems, where one nozzle costs approximately 5000 USD excluding cost for installation time.

8.4 Other Areas of Interest

Though a complete cost-benefit analysis has not been performed within this thesis some high-risk and high-cost areas, apart from those discussed in previous sections, have been identified as potential targets where risk control measures could be profitable.

As discussed in Section 6.3 the repair time is believed to greatly affect the financial costs of a fire and/or explosion damage, due to both high costs in relation to taking a ship out of service (e.g. daily income losses) and actual repair costs (machinery and man-hours). By giving the crew better means of carrying out repairs or by having a well developed plan for how to efficiently deal with the effects of a fire and/or explosion incident there is potentially large amounts of money to be saved.

Furthermore it is noted that other actions, not specifically taken into account in the risk model, such as towing of a ship to port can quickly amount to huge costs. Similar to the above, and as discussed further in Section 6.3.3, in advance drawn up contracts or plans of action could prove to be a major cost saving when an incident occurs.

In the sensitivity analysis, as described in Section 7.3, it is concluded that the probabilities of succeeding with the different fire extinguishing efforts will always be of great importance. Naturally the damages are usually smaller the sooner the fire is extinguished and if a total loss (constructive or sinking) can be avoided it will of course be advantageous. Therefore any counter measures that improve the reliability and effectiveness of the extinguishing systems, some examples are given in Section 8.3, would be worth investigating further.

9 Discussion and Conclusions

This section summarises the thesis with discussions on the contents of the report and its findings, and ends with conclusions that relate to the objectives stated in the beginning of the thesis.

9.1 Discussion

The aim of this thesis has been to investigate fires and explosions in machinery spaces on oil tankers and container vessels. Since the topic is quite specific and limited work has been done on the subject it has been difficult to find relevant information. Therefore we had to use information from other papers and reports where the vessel types did not always match the ones of interest for this thesis. Given this our findings, i.e. the Thesis Database Search, interviews and visits on board ships were assigned higher relevance than other sources.

The approach used in this thesis differs a bit from other reports, such as those by MEPC (2008) or MSC (2007*b*). A risk analysis following the exact FSA guidelines tends to include all possible risks for a given type of ships, where fire in general is only one of several risk categories. Therefore not much attention is given to the specific fire risks aboard, such as fires in the machinery space. Within this thesis fires and explosions in the machinery space are isolated from other risks and only causes and consequences of these specific risks are considered. As an example Aksu, Delautre, Eliopoulou, Mikeils & Papanikolaou (2006) gives an expected accident rate of 3.81×10^{-2} per shipyear for all incidents on AFRAMAX tankers. With 10% of those being fires it shows that our findings are fairly similar with respect to the expected incident frequency. The focus of this thesis has been to investigate the consequences of these fires or explosions and to calculate an expected loss both in terms of financial loss and personal injuries/fatalities.

The approach to calculate the costs and frequencies in this thesis is considered suitable with respect to the initial problem, since it incorporates uncertainties in terms of distributions in almost every parameter used which gives intervals instead of just mean values as results. However it has proven difficult to find accurate values for costs for such a large span of ships, given that each ship in the fleet is unique with respect to size, age, machinery layout etc. But although it has been hard to find specific representative numbers, especially for financial costs, the risk model allows for easy adjustments to refine the input data and get more exact results if necessary. Hence, the financial losses differ widely depending on various factors, most of them difficult to model, and even a seemingly small fire extinguished by a portable fire extinguisher could, under unfortunate circumstances, induce far greater losses then a bigger fire in a less critical place and/or under more favourable conditions.

One major factor affecting the cost for repairing the ship after fire or explosion damage is the time it takes to return the ship to normal operating conditions; especially if the ship has to be laid up at a dry dock the off hire costs adds rather quickly to large sums. It is therefore crucial to reduce the repair time once the ship has to be laid up. This is why many ship owners would prefer to let the crew on board the ship repair smaller/medium non-urgent damages during normal operation where possible. One cost that has not been specifically taken into account when determining the total financial losses is the cost for towing the ship to port in case of loss of propulsion machinery and/or steering equipment. This cost is mainly believed to influence the cost of a total ship loss, i.e. in case of a constructive total loss, but towing assistance can of course be necessary even after smaller fires and/or explosions, depending on the circumstances. Especially in an emergency (e.g. if pollution is an issue, or when the ship is close to a coastline) where time is of great importance the costs can quickly amount to hundreds of thousands USD. To cooperate with towing/repair companies or to have specific agreements laid out at forehand could potentially save a lot of time and money once an incident occurs.

The information gathered provides a good overview of risks associated with fires and explosions in machinery spaces. However it is noted that a more detailed analysis would benefit from even more information in the databases. It was noted that there were a lot of different fields to fill out but in many cases these were left out, and often one or two more sentences would be a major improvement (e.g. *the fire started in... due to...* instead of just *in engine room*). Since information and knowledge is a big or even the main competitive factor in the shipping industry (amongst classifications societies and others) it may be a sensitive area with confidentiality always being a key issue, but it is difficult to disregard the fact that everybody would benefit from better and more accurate results from studies like these.

As discussed in the FSA for Container Vessels (MSC 2007*b*) some underreporting most likely exist within the shipping industry, which affects the reliability of the statistical data. It is believed that the underreporting is mainly a problem for minor incidents, whereas the problem is less widespread with respect to major incidents where the consequences are greater. Fatal accidents are for example believed to be reported and well investigated in most cases, whereas minor personal injuries do not receive the same attention. Though not resulting in major consequences at the time, even minor incidents could serve to improve the safety as a whole, by indicating in which areas errors or failures (that might under certain circumstances lead to severe fires and/or explosions) are likely to occur. Therefore it is of great importance that even smaller incidents or near-accidents are taken seriously and reported.

Within the risk analysis in this thesis one assumption was made with respect to the course of action after a fire and/or explosion has occurred. The risk model is constructed in consideration to these simplifications, which have also affected the estimated effectiveness of the different extinguishing systems to some degree. For example is a fire fighting effort believed to be the last resort to completely put out a fire after the CO_2 system has been released. Therefore the probability of a successful fire fighting effort is assumed greater (since the CO_2 has most likely suppressed the fire even though it is not fully extinguished) than if the fire was fully developed at the entering point of the fire fighters. This has of course affected the results to a certain extent. However, even though the systems interact and that it is difficult to specify what is the most crucial factor in extinguishing a fire, it is believed that the entire chain of events is of greater importance for the final results rather than the order in which the systems are used.

9.2 Conclusions

The aim of this thesis has been as follows:

> *What are the main risks, and the financial and personal losses of these risks, with respect to fire and explosion in machinery spaces on oil tankers and container vessels, and how can these risks be reduced or eliminated by practical and reasonable means?*

By developing a risk model we have concluded that the expected frequency of a fire and/or explosion in the machinery space of oil tankers and container vessels is 2.50×10^{-3} (with a $\mathrm{CI}_{90\%}(1.58 - 3.84) \times 10^{-3}$) per shipyear. For the entire world fleet of oil tankers and container vessels the expected frequency of fires and/or explosions is 12.6 incidents annually. The most critical components, where a failure could lead to a fire and/or explosion, are boilers, generators and leaking pumps.

Given a fire and/or explosion that does not result in a total loss of the ship the expected financial loss amounts to 300,000 USD ($\mathrm{CI}_{90\%}(1,000,000 - 2,000,000)$ USD). With respect to the risks for the crew the probability of one or more fatalities, given an incident, is 0.07 ($\mathrm{CI}_{90\%}(0.04 - 0.10)$). For the entire world fleet a loss of 1.5 lives is expected per year.

A calculation was made on replacing the CO_2 system by a full coverage sprinkler system, which would reduce the expected financial losses by 28,000 USD in total during a ship lifetime ($\mathrm{CI}_{90\%}(49,000 - 69,000)$ USD). Hence, the cost of replacing the system must fall below this amount for the investment to be beneficial. Or alternatively when choosing system for a newbuild the sprinkler system should not cost more than this in comparison to the CO_2 system. This could be hard to fulfil with regard to the sprinkler system already being 45% more expensive (as stated by af Schmidt (2009)).

The model developed uses an approach believed suitable for this kind of analysis but is highly dependent on the accuracy of the input parameters. It has been difficult to estimate things such as costs since even experts consulted within the field agree that it is nearly impossible to give general estimates. Furthermore the incident reports did not provide sufficient detail on how the fires were extinguished whereby other sources, less specific with respect to ship type, had to be used.

In order to perform a complete risk analysis and especially a cost-benefit analysis, using our model it is necessary to find more specific counter measures and quantify the effect on how these lower the probabilities of loss or how they affect the risk of a fire and/or explosion in the machinery space. Furthermore a cost assessment on the installation and maintenance of these measures would be needed. As discussed in this thesis this would be very difficult to do for a generic ship and more suitable for a specific ship where accurate data is possible to get.

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A Statistical Data On Fleet Sizes

Table A.1: Statistical data for the world fleet and GL fleet receptively. Some of the numbers (i.e. Stroke, Engine or Speed) are not calculated on the total due to lack of information in the LRF (2009b) database.

Type	Unit	Median	Average	Min	Max
World container ships (4825 in total)					
Age	years	7.5	10.3	0.1	60.3
GT	-	32,629	29,825	355	170,794
LOA	m	222	202	50	398
Depth	m	19	16	4	30
TEU	-	2816	2622	73	14,000
Engine Stroke	-	2	-	-	-
Engine Power	kW	22,175	21,905	552	81,254
Speed	knots	22.0	20.4	9.2	29.2
Building Price	$\times 10^3$ USD	44,000	43,346	2710	150,000
GL container ships (2113 in total)					
Age	years	6.7	8.5	0.1	39.8
GT	-	18,327	26,998	2077	151,559
LOA	m	182	195	98	366
Depth	m	15	16	6	30
TEU	-	1730	2456	190	14,000
Engine Stroke	-	2	-	-	-
Engine Power	kW	14,268	20,361	1292	74,760
Speed	knots	20.0	20.4	12.0	27.4
Building Price	$\times 10^3$ USD	35,000	39,838	4400	150,000
World tanker ships (7732 in total)					
Age	years	18.3	21.5	0.1	107.5
GT	-	3236	26,684	84	234,006
LOA	m	105	145	25	380
Depth	m	7	12	2	38
Engine Stroke	-	4	-	-	-
Engine Power	kW	2207	6054	74	81,700
Speed	knots	13.2	12.8	4.0	23.0
Building Price	$\times 10^3$ USD	40,658	46,434	1384	427,000
GL tanker ships (122 in total)					
Age	years	18.8	18.8	0.1	51.7
GT	-	2282	16,391	123	161,306
LOA	m	93	122	35	333
Depth	m	6	10	2	30
Engine Stroke	-	4	-	-	-
Engine Power	kW	1618	4694	169	26,412
Speed	knots	12.0	12.5	8.0	17.0
Building Price	$\times 10^3$ USD	29,095	30,686	4836	52,000

*Table A.2: Statistical data for the world fleet and GL fleet receptively for ships delivered after 1 January 1998. Some of the numbers (i.e. Stroke, Engine or Speed) are not calculated on the total due to lack of information in the LRF (2009*b*) database.*

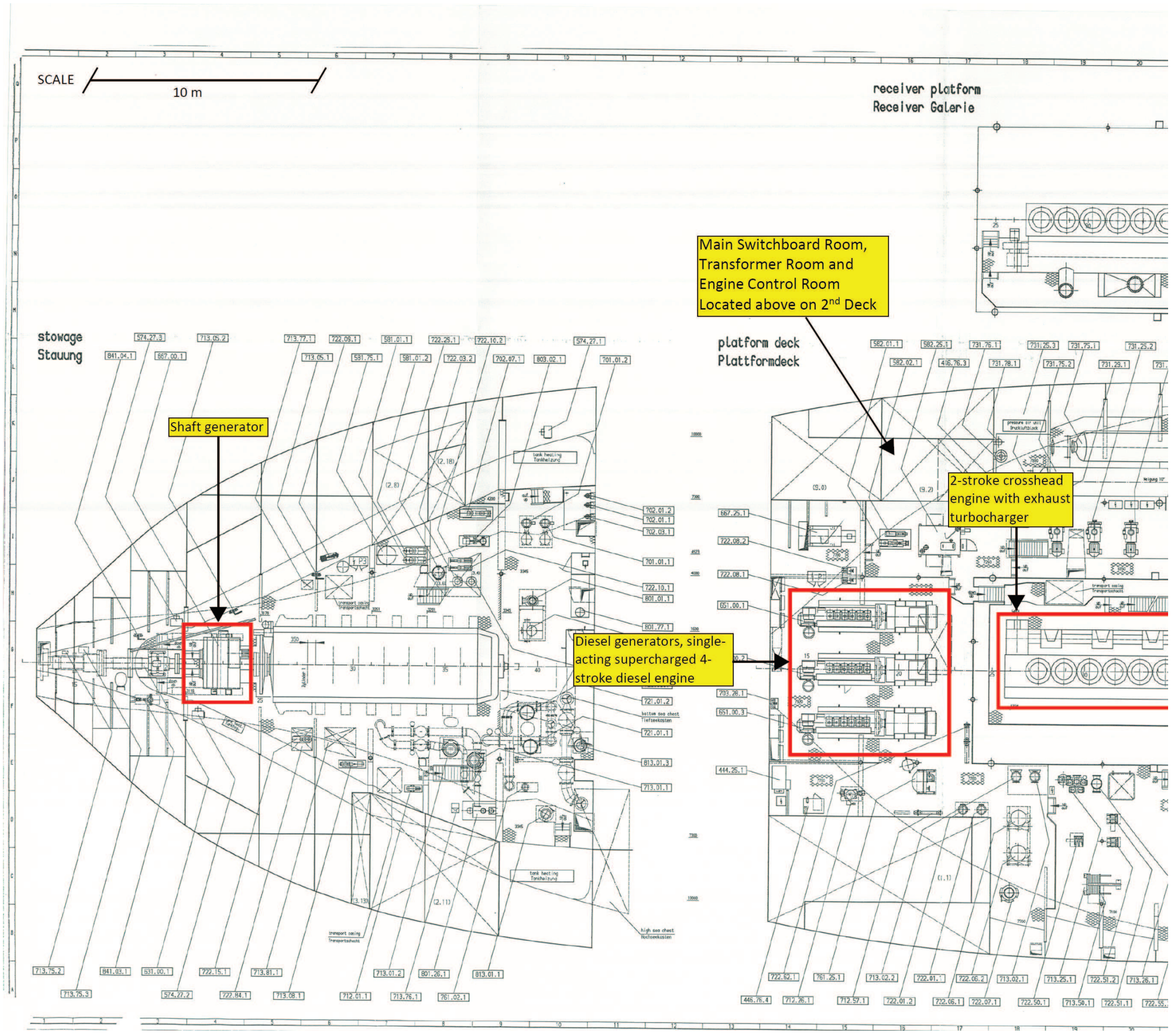
	Unit	Median	Average	Min	Max
World container ships (2526 in total) Shipyears in total 12,897.9					
Age	years	3.6	4.4	0.1	11.1
GT	-	26,131	34,868	355	170,794
LOA	m	208	215	50	398
Depth	m	17	17	4	30
TEU	-	2500	3163	80	14,000
Engine Stroke	-	2	-	-	-
Engine Power	kW	20,930	26,848	668	81,254
Speed	knots	22.0	21.5	9.2	29.2
Building Price	×10^3 USD	42,000	47,158	9,000	150,000
GL container ships (1453 in total) Shipyears in total 6464.4					
Age	years	3.6	4.4	0.1	11.1
GT	-	25,361	30,950	2077	151,559
LOA	m	200	206	100	366
Depth	m	16	16	6	30
TEU	-	2262	2846	190	14,000
Engine Stroke	-	2	-	-	-
Engine Power	kW	18,504	23,769	1,292	74,760
Speed	knots	21.3	21.2	13.0	26.4
Building Price	×10^3 USD	39,000	42,103	13,000	150,000
World tanker ships (2520 in total) Shipyears in total 11,916.2					
Age	years	4.5	4.7	0.1	11.1
GT	-	42,010	53,239	101	234,006
LOA	m	21	18	2	38
Depth	m	602	442	116	608
Engine Stroke	-	2	-	-	-
Engine Power	kW	11,041	11,420	132	72,420
Speed	knots	15.0	14.4	6.0	23.0
Building Price	×10^3 USD	43,000	50,573	6000	210,000
GL tanker ships (46 in total) Shipyears in total 267.8					
Age	years	6.3	5.8	0.1	10.9
GT	-	19,006	32,274	365	161,306
LOA	m	185	182	40	333
Depth	m	17	16	3	30
Engine Stroke	-	4	-	-	-
Engine Power	kW	8385	9272	736	26,412
Speed	knots	15.0	14.3	9.5	17.0
Building Price	×10^3 USD	52,000	45,143	30,000	52,000

*Table A.3: Total shipyears for oil tanker and container fleets. All ships that have been in operation during the last 11 years have been included. (LRF 2009*b*)*

Fleet	All ages	Delivered 1998 or later
Container	58,748	12,898
Container GL	18,780	6464
Oil Tanker	210,422	11,916
Oil Tanker GL	2534	268

B Drawings

Two drawings over the machinery space for the generic ship *M/S Thesis* are shown on the following pages.


SCALE
10 m
receiver platform
Receiver Galerie
Main Switchboard Room, Transformer Room and Engine Control Room Located above on 2nd Deck
stowage
Stauung
platform deck
Plattformdeck
Shaft generator
2-stroke crosshead engine with exhaust turbocharger
Diesel generators, single-acting supercharged 4-stroke diesel engine
tank heating
Tankheizung
transport casing
Transportschacht
bottom sea chest
Tiefseekasten
high sea chest
Hochseekasten
pressure air unit
Druckluftstation

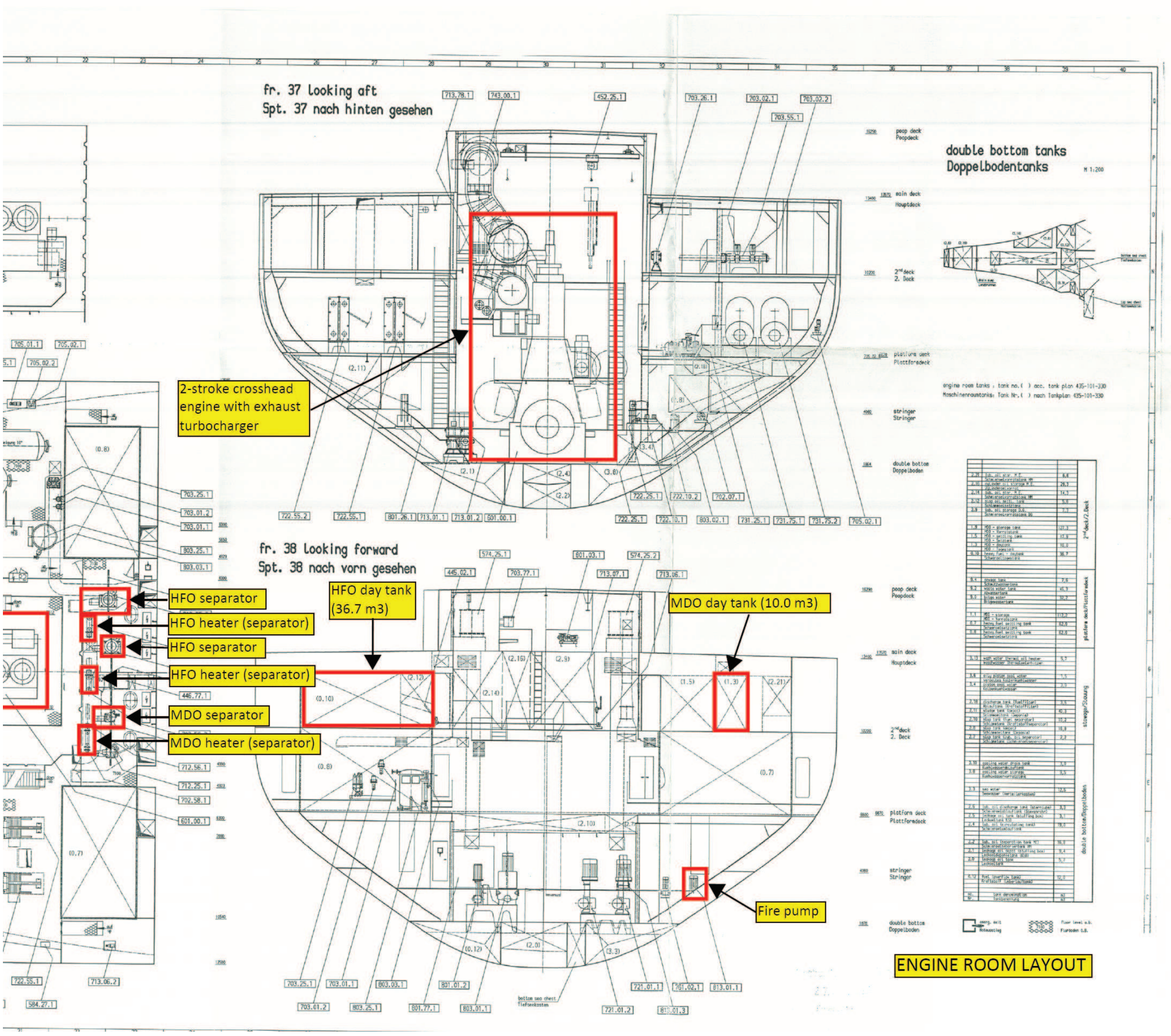
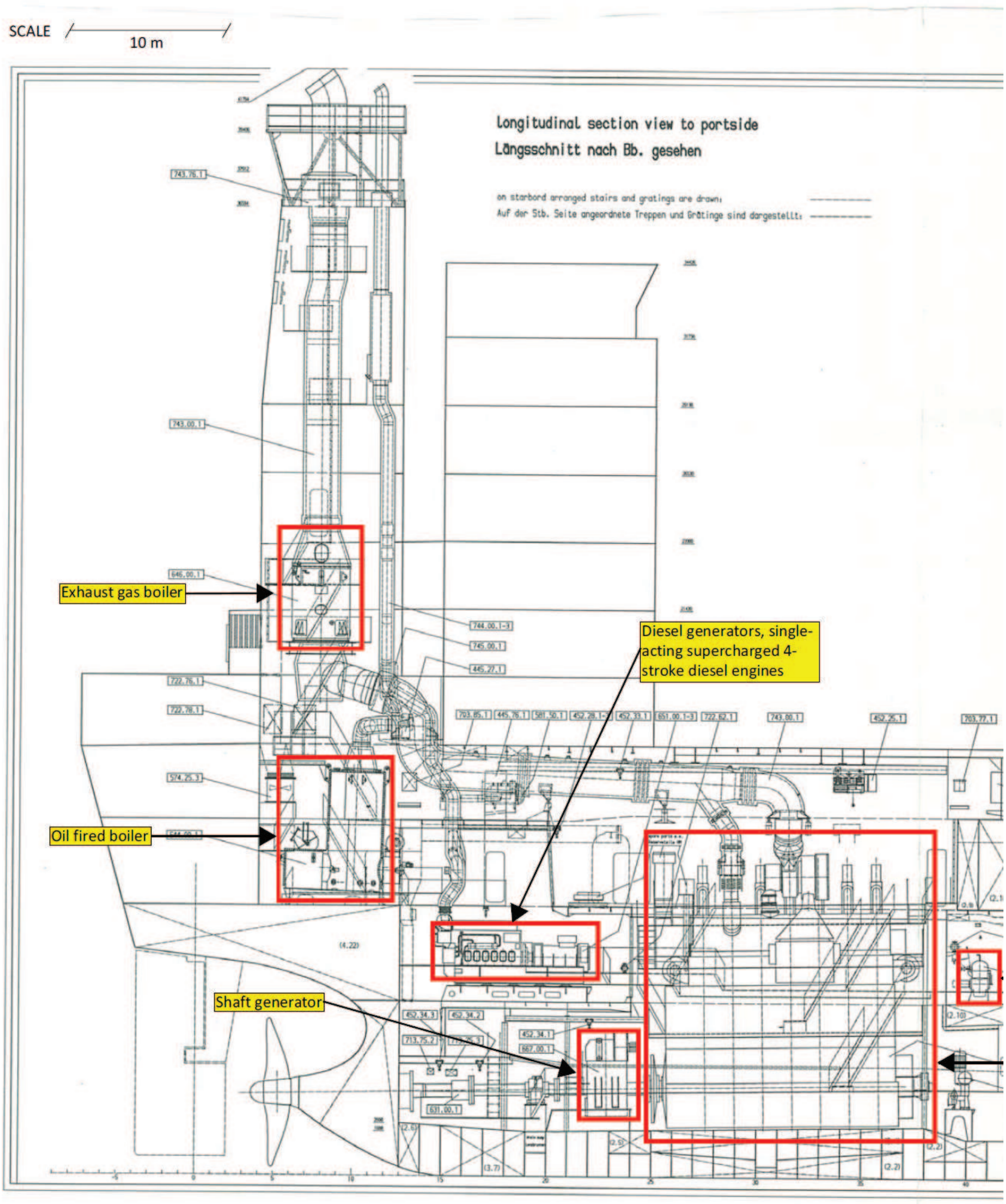


Figure B.1: Machinery space layout of M/S Thesis *with a two stroke engine as seen from a top view, looking aft and forward, slightly modified to highlight the most relevant parts (Kvaerner 1995).*


SCALE
10 m
Longitudinal section view to portside
Längsschnitt nach Bb. gesehen
on starbord arranged stairs and gratings are drawn:
Auf der Stb. Seite angeordnete Treppen und Grätinge sind dargestellt:
Exhaust gas boiler
Oil fired boiler
Diesel generators, single-acting supercharged 4-stroke diesel engines
Shaft generator
743.76.1
743.00.1
646.00.1
744.00.1-3
745.00.1
445.77.1
722.76.1
722.78.1
574.25.3
713.75.2
452.34.3
452.34.2
452.34.1
667.00.1
631.00.1
743.00.1
452.25.1
703.77.1
(4.22)

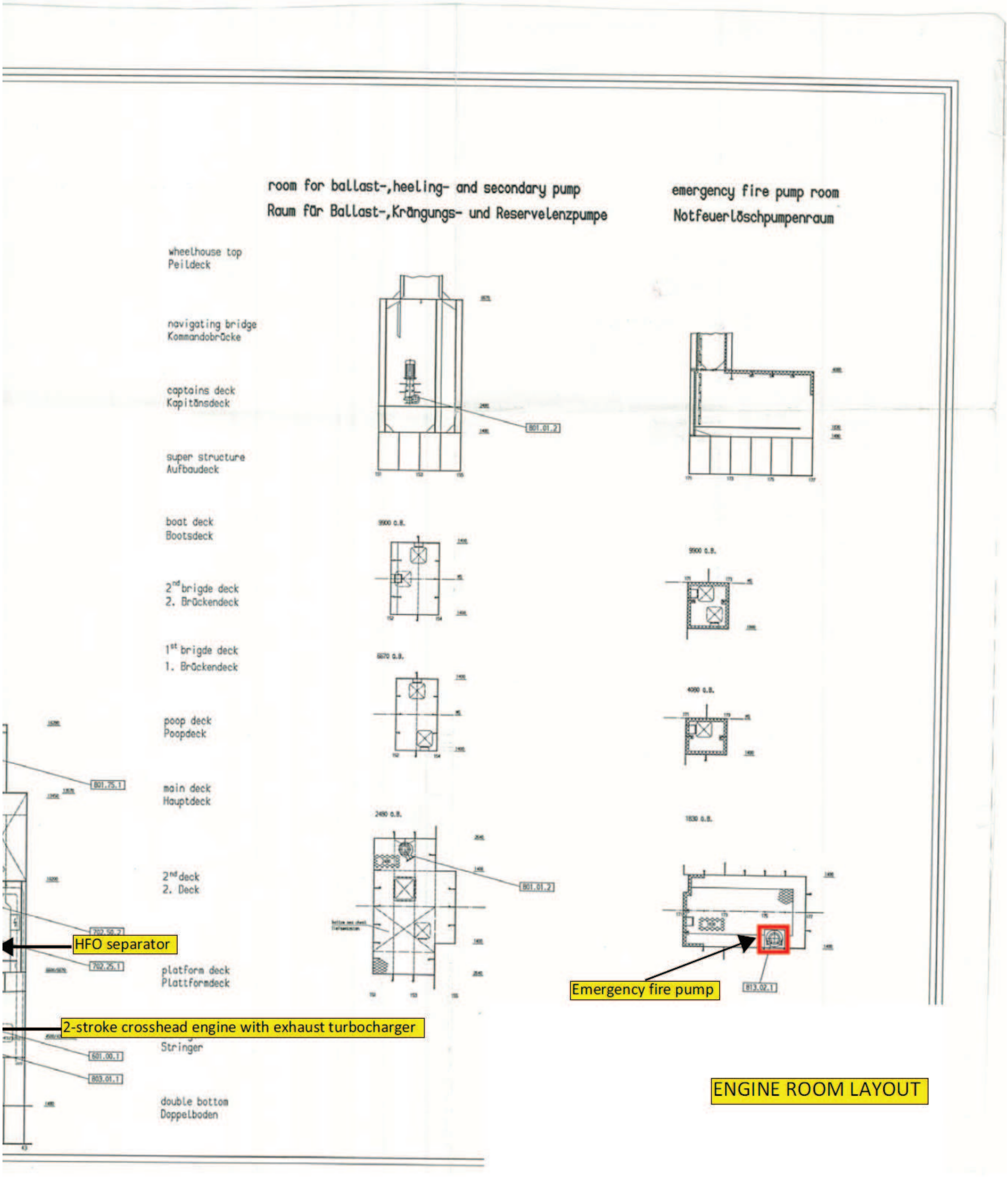


Figure B.2: Machinery space layout of M/S Thesis *with a two stroke engine as seen from a longitudinal section view to portside, slightly modified to highlight the most relevant parts (Kvaerner 1995).*

C Risk Model

Explosion	Fire	Detection	Portable	Sprinkler	CO_2	Fire Fighting	Cost	Branch ID
Yes	Yes	None	-	-	-	-	Minor	/1/1/0/-/-/-/-/1/
		+	-	-	-	-	Major	/1/1/0/-/-/-/-/2/
	+	Early	Yes	-	-	-	Minor	/1/1/1/1/-/-/-/1/
			+	-	-	-	Major	/1/1/1/1/-/-/-/2/
		+	No	Yes	-	-	Minor	/1/1/1/0/1/-/-/1/
				+	-	-	Major	/1/1/1/0/1/-/-/2/
			+	No	Yes	-	Minor	/1/1/1/0/0/1/-/1/
					+	-	Major	/1/1/1/0/0/1/-/2/
				+	No	Yes	Minor	/1/1/1/0/0/0/1/1/
						+	Major	/1/1/1/0/0/0/1/2/
						No	Minor	/1/1/1/0/0/0/0/1/
						+	Major	/1/1/1/0/0/0/0/2/
	+	Late	Yes	-	-	-	Minor	/1/1/2/1/-/-/-/1/
			+	-	-	-	Major	/1/1/2/1/-/-/-/2/
		+	No	Yes	-	-	Minor	/1/1/2/0/1/-/-/1/
				+	-	-	Major	/1/1/2/0/1/-/-/2/
			+	No	Yes	-	Minor	/1/1/2/0/0/1/-/1/
					+	-	Major	/1/1/2/0/0/1/-/2/
				+	No	Yes	Minor	/1/1/2/0/0/0/1/1/
						+	Major	/1/1/2/0/0/0/1/2/
					+	No	Minor	/1/1/2/0/0/0/0/1/
						+	Major	/1/1/2/0/0/0/0/2/
+	No	-	-	-	-	-	Minor	/1/0/-/-/-/-/-/1/
	+	-	-	-	-	-	Major	/1/0/-/-/-/-/-/2/

Figure C.1: Schematic figure over the event tree model used (explosion branch). Each cost branch can represent financial, safety or environmental costs. For notations used for branch ID see Section 4.2.

Explosion	Fire	Detection	Portable	Sprinkler	CO$_2$	Fire Fighting	Cost	Branch ID
No	Yes	None	-	-	-	-	Minor	/0/1/0/-/-/-/-/1/
		+	-	-	-	-	Major	/0/1/0/-/-/-/-/2/
	+	Early	Yes	-	-	-	Minor	/0/1/1/1/-/-/-/1/
			+	-	-	-	Major	/0/1/1/1/-/-/-/2/
		+	No	Yes	-	-	Minor	/0/1/1/0/1/-/-/1/
				+	-	-	Major	/0/1/1/0/1/-/-/2/
			+	No	Yes	-	Minor	/0/1/1/0/0/1/-/1/
					+	-	Major	/0/1/1/0/0/1/-/2/
				+	No	Yes	Minor	/0/1/1/0/0/0/1/1/
						+	Major	/0/1/1/0/0/0/1/2/
						No	Minor	/0/1/1/0/0/0/0/1/
						+	Major	/0/1/1/0/0/0/0/2/
	+	Late	Yes	-	-	-	Minor	/0/1/2/1/-/-/-/1/
			+	-	-	-	Major	/0/1/2/1/-/-/-/2/
		+	No	Yes	-	-	Minor	/0/1/2/0/1/-/-/1/
				+	-	-	Major	/0/1/2/0/1/-/-/2/
			+	No	Yes	-	Minor	/0/1/2/0/0/1/-/1/
					+	-	Major	/0/1/2/0/0/1/-/2/
				+	No	Yes	Minor	/0/1/2/0/0/0/1/1/
						+	Major	/0/1/2/0/0/0/1/2/
					+	No	Minor	/0/1/2/0/0/0/0/1/
						+	Major	/0/1/2/0/0/0/0/2/
+	No	-	-	-	-	-	-	/0/0/-/-/-/-/-/-/

Figure C.2: Schematic figure over the event tree model used (no explosion branch). Each cost branch can represent financial, safety or environmental costs. For notations used for branch ID see Section 4.2.

D Hazard Identification

Table D.1: Data from the simulation of the OREDA frequency of fire and/or explosion incidents in machinery spaces.

OREDA	$\times 10^{-5}$
Minimum	25.30
Mean	143.62
Maximum	446.80
Std Dev	70.16
Variance	0.49
5th Perc.	51.91
95th Perc.	278.57

Table D.2: Data from the simulation of the final frequency of fire and/or explosion incidents in machinery spaces.

TOTAL	$\times 10^{-5}$
Minimum	13.22
Mean	28.92
Maximum	63.55
Std Dev	7.51
Variance	0.01
5th Perc.	18.28
95th Perc.	42.68

E Consequence Analysis

E.1 Failure Rate

Table E.1: Distributions for factors used in the frequency analysis.

Factor	Value	
Critical Leakage	0.01	U(0.005; 0.015)
Hot Surface	0.03	U(0.01; 0.05)
Other Ignition Source	1.275	U(1.08; 1.47)

Table E.2: Distributions for components used in the frequency analysis.

Component	Leakage Failure Rate ±10%		Number of Components	
Pumps	0.310	T(0.279; 0.310; 0.341)	18	T(11; 18; 25)
Boiler	0.032	T(0.029; 0.032; 0.035)	2.7	T(2; 2; 4)
Generator	0.021	T(0.019; 0.021; 0.023)	3.3	T(3; 3; 4)
Main engine	0.194	T(0.174; 0.194; 0.213)	1	-
Separators	0.104	T(0.094; 0.104; 0.114)	6	T(4; 6; 8)
Valves	0.257	T(0.231; 0.257; 0.282)	300	T(200; 300; 400)

E.2 Consequences

Table E.3: Distribution table for each branch. The actual distributions can be found in Table E.4 for probabilities and in Table E.5 for costs. For notations used for branch ID see Section 4.2.

Branch	Probability	Financial Prob.	Financial Cost	Safety Prob.	Safety Cost
/1/1/0/-/-/-/-/1/		$\mathrm{FI_p}1$	$\mathrm{FI_c}6$	$\mathrm{SA_p}1$	$\mathrm{SA_c}1$
/1/1/0/-/-/-/-/-/	D1				
/1/1/0/-/-/-/-/2/		1-$\mathrm{FI_p}1$	$\mathrm{FI_c}1$	1-$\mathrm{SA_p}1$	$\mathrm{SA_c}1$
/1/1/-/-/-/-/-/-/	F2				
/1/1/1/1/-/-/-/1/		$\mathrm{FI_p}3$	$\mathrm{FI_c}9$	$\mathrm{SA_p}2$	$\mathrm{SA_c}3$
/1/1/1/1/-/-/-/-/	P1				
/1/1/1/1/-/-/-/2/		1-$\mathrm{FI_p}3$	$\mathrm{FI_c}1$	1-$\mathrm{SA_p}2$	$\mathrm{SA_c}2$
/1/1/1/-/-/-/-/-/	D2				
/1/1/1/0/1/-/-/1/		$\mathrm{FI_p}4$	$\mathrm{FI_c}9$	$\mathrm{SA_p}3$	$\mathrm{SA_c}3$
/1/1/1/0/1/-/-/-/	S1				
/1/1/1/0/1/-/-/2/		1-$\mathrm{FI_p}4$	$\mathrm{FI_c}1$	1-$\mathrm{SA_p}3$	$\mathrm{SA_c}2$
/1/1/1/0/-/-/-/-/	1-P1				
/1/1/1/0/0/1/-/1/		$\mathrm{FI_p}6$	$\mathrm{FI_c}12$	$\mathrm{SA_p}4$	$\mathrm{SA_c}3$
/1/1/1/0/0/1/-/-/	C1				
/1/1/1/0/0/1/-/2/		1-$\mathrm{FI_p}6$	$\mathrm{FI_c}1$	1-$\mathrm{SA_p}4$	$\mathrm{SA_c}2$
/1/1/1/0/0/-/-/-/	1-S1				
/1/1/1/0/0/0/1/1/		$\mathrm{FI_p}7$	$\mathrm{FI_c}15$	$\mathrm{SA_p}5$	$\mathrm{SA_c}3$
/1/1/1/0/0/0/1/-/	FF1				
/1/1/1/0/0/0/1/2/		1-$\mathrm{FI_p}7$	$\mathrm{FI_c}1$	1-$\mathrm{SA_p}5$	$\mathrm{SA_c}2$
/1/1/1/0/0/0/-/-/	1-C1				
/1/1/1/0/0/0/0/1/		$\mathrm{FI_p}2$	$\mathrm{FI_c}2$	$\mathrm{SA_p}6$	$\mathrm{SA_c}3$
/1/1/1/0/0/0/0/-/	1-FF1				
/1/1/1/0/0/0/0/2/		1-$\mathrm{FI_p}2$	$\mathrm{FI_c}1$	1-$\mathrm{SA_p}6$	$\mathrm{SA_c}2$
/1/1/2/1/-/-/-/1/		$\mathrm{FI_p}3$	$\mathrm{FI_c}9$	$\mathrm{SA_p}2$	$\mathrm{SA_c}3$
/1/1/2/1/-/-/-/-/	P2				
/1/1/2/1/-/-/-/2/		1-$\mathrm{FI_p}3$	$\mathrm{FI_c}1$	1-$\mathrm{SA_p}2$	$\mathrm{SA_c}2$
/1/1/2/-/-/-/-/-/	1-D1-D2				
/1/1/2/0/1/-/-/1/		$\mathrm{FI_p}4$	$\mathrm{FI_c}9$	$\mathrm{SA_p}3$	$\mathrm{SA_c}3$
/1/1/2/0/1/-/-/-/	S1				
/1/1/2/0/1/-/-/2/		1-$\mathrm{FI_p}4$	$\mathrm{FI_c}1$	1-$\mathrm{SA_p}3$	$\mathrm{SA_c}2$
/1/1/2/0/-/-/-/-/	1-P2				
/1/1/2/0/0/1/-/1/		$\mathrm{FI_p}6$	$\mathrm{FI_c}12$	$\mathrm{SA_p}4$	$\mathrm{SA_c}3$
/1/1/2/0/0/1/-/-/	C1				
/1/1/2/0/0/1/-/2/		1-$\mathrm{FI_p}6$	$\mathrm{FI_c}1$	1-$\mathrm{SA_p}4$	$\mathrm{SA_c}2$
/1/1/2/0/0/-/-/-/	1-S1				

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Table E.3 Continuation from previous page

Branch	Probability	Financial Prob.	Financial Cost	Safety Prob.	Safety Cost
/1/1/2/0/0/0/1/1/		FI$_p$7	FI$_c$15	SA$_p$5	SA$_c$3
/1/1/2/0/0/0/1/-/	FF1				
/1/1/2/0/0/0/1/2/		1-FI$_p$7	FI$_c$1	1-SA$_p$5	SA$_c$2
/1/1/2/0/0/0/-/-/	1-C1				
/1/1/2/0/0/0/0/1/		FI$_p$2	FI$_c$2	SA$_p$6	SA$_c$3
/1/1/2/0/0/0/0/-/	1-FF1				
/1/1/2/0/0/0/0/2/		1-FI$_p$2	FI$_c$1	1-SA$_p$6	SA$_c$2
/1/-/-/-/-/-/-/-/	E1				
/1/0/-/-/-/-/-/1/		FI$_p$5	FI$_c$16	SA$_p$12	SA$_c$3
/1/0/-/-/-/-/-/-/	1-F2				
/1/0/-/-/-/-/-/2/		1-FI$_p$5	FI$_c$1	1-SA$_p$12	SA$_c$2
/0/1/0/-/-/-/-/1/		FI$_p$1	FI$_c$6	SA$_p$1	SA$_c$1
/0/1/0/-/-/-/-/-/	D3				
/0/1/0/-/-/-/-/2/		1-FI$_p$1	FI$_c$1	1-SA$_p$1	SA$_c$1
/0/1/-/-/-/-/-/-/	F1				
/0/1/1/1/-/-/-/1/		FI$_p$3	FI$_c$9	SA$_p$7	SA$_c$3
/0/1/1/1/-/-/-/-/	P3				
/0/1/1/1/-/-/-/2/		1-FI$_p$3	FI$_c$1	1-SA$_p$7	SA$_c$2
/0/1/1/-/-/-/-/-/	D4				
/0/1/1/0/1/-/-/1/		FI$_p$4	FI$_c$9	SA$_p$8	SA$_c$3
/0/1/1/0/1/-/-/-/	S1				
/0/1/1/0/1/-/-/2/		1-FI$_p$4	FI$_c$1	1-SA$_p$8	SA$_c$2
/0/1/1/0/-/-/-/-/	1-P3				
/0/1/1/0/0/1/-/1/		FI$_p$8	FI$_c$12	SA$_p$9	SA$_c$3
/0/1/1/0/0/1/-/-/	C1				
/0/1/1/0/0/1/-/2/		1-FI$_p$8	FI$_c$1	1-SA$_p$9	SA$_c$2
/0/1/1/0/0/-/-/-/	1-S1				
/0/1/1/0/0/0/1/1/		FI$_p$9	FI$_c$15	SA$_p$10	SA$_c$3
/0/1/1/0/0/0/1/-/	FF1				
/0/1/1/0/0/0/1/2/		1-FI$_p$9	FI$_c$1	1-SA$_p$10	SA$_c$2
/0/1/1/0/0/0/-/-/	1-C1				
/0/1/1/0/0/0/0/1/		FI$_p$2	FI$_c$2	SA$_p$11	SA$_c$3
/0/1/1/0/0/0/0/-/	1-FF1				
/0/1/1/0/0/0/0/2/		1-FI$_p$2	FI$_c$1	1-SA$_p$11	SA$_c$2
/0/1/2/1/-/-/-/1/		FI$_p$3	FI$_c$9	SA$_p$7	SA$_c$3
/0/1/2/1/-/-/-/-/	P4				
/0/1/2/1/-/-/-/2/		1-FI$_p$3	FI$_c$1	1-SA$_p$7	SA$_c$2
/0/1/2/-/-/-/-/-/	1-D3-D4				
/0/1/2/0/1/-/-/1/		FI$_p$4	FI$_c$9	SA$_p$8	SA$_c$3

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Table E.3 Continuation from previous page

Branch	Probability	Financial Prob.	Financial Cost	Safety Prob.	Safety Cost
/0/1/2/0/1/-/-/-/	S1				
/0/1/2/0/1/-/-/2/		1-FI_p4	FI_c1	1-SA_p8	SA_c2
/0/1/2/0/-/-/-/-/	1-P4				
/0/1/2/0/0/1/-/1/		FI_p8	FI_c12	SA_p9	SA_c3
/0/1/2/0/0/1/-/-/	C1				
/0/1/2/0/0/1/-/2/		1-FI_p8	FI_c1	1-SA_p9	SA_c2
/0/1/2/0/0/-/-/-/	1-S1				
/0/1/2/0/0/0/1/1/		FI_p9	FI_c15	SA_p10	SA_c3
/0/1/2/0/0/0/1/-/	FF1				
/0/1/2/0/0/0/1/2/		1-FI_p9	FI_c1	1-SA_p10	SA_c2
/0/1/2/0/0/0/-/-/	1-C1				
/0/1/2/0/0/0/0/1/		FI_p2	FI_c2	SA_p11	SA_c3
/0/1/2/0/0/0/0/-/	1-FF1				
/0/1/2/0/0/0/0/2/		1-FI_p2	FI_c1	1-SA_p11	SA_c2
/0/-/-/-/-/-/-/-/	1-E1				
/0/0/-/-/-/-/-/-/	1-F1				

Table E.4: Distribution table for probabilities of events. Events appear in same order as in the branches (i.e. /Explosion/Fire/ Detection/Portable/Sprinkler/CO$_2$/Fire Fighting/Cost/). For notations used for distributions and branch ID see Section 4.2. The distributions are motivated in Section 6.

		Branch/-es							
	Distribution	Explosion	Fire	Detection	Portable	Sprinkler	CO$_2$	Fire Fighting	Cost
	Explosion								
E1	T(0.118, 0.168, 0.202)	1	-	-	-	-	-	-	-
	(0.17 30/20) Percentage explosions out of incidents, based on Thesis Database Search and NK Report.								
	Fire								
F1	1	0	1	-	-	-	-	-	-
	Only possible outcome, a scenario without an explosion and without a fire falls outside the scope of investigation.								
F2	T(0.667, 0.833, 1)	1	1	-	-	-	-	-	-
	(0.83 20/20) Percentage of explosions being followed by fires, based on Thesis Database Search and NK (1994) report.								
	Detection								
D1	0	1	1	0	-	-	-	-	-
	An explosion is believed to be noticed, either manually or by machinery failure indication, and a following fire will therefore be detected.								
D3	T(0.6, 0.75, 0.9)	1	1	1	-	-	-	-	-
	(0.75 20/20) 3/4 of all fires following explosions are considered to be detected early, due to faster fire growth and other means of detection (e.g. failure indications from machinery causing explosion)								
D3	U(0, 0.1)	0	1	0	-	-	-	-	-
	(0-0.1) Assumption of non-detected fires based on personal judgements and statistical data								
D4	T(0.8×(1-D4)/2, (1-D4) /2, 1.2×(1-D4)/2)	0	1	1	-	-	-	-	-
	((1-D3)/2 20/20) Half of all detected fires without initial explosion are believed to be detected early.								

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Table E.4 Continuation from previous page

		Branch/-es							
	Distribution	Explosion	Fire	Detection	Portable	Sprinkler	CO_2	Fire Fighting	Cost
	Portable extinguisher								
P1	T(0, 0.2, 0.4) (0.2 100/100) Due to initial explosion lower probability of extinguishing fire by portable means than NK (1994) report.	1	1	1	1	-	-	-	-
P2	T(0, 0.1, 0.2) (0.1 100/100) Due to late detection considerably lower probability of extinguishing fire by portable means than NK (1994) report.	1	1	2	1	-	-	-	-
P3	T(0.35, 0.5, 0.55) (0.5 30/10) Higher probability of succeeding compared to NK (1994) report due to early detection.	0	1	1	1	-	-	-	-
P4	T(0, 0.1, 0.2) (0.1 100/100) Due to late detection considerably lower probability of extinguishing fire by portable means than NK (1994) report.	0	1	2	1	-	-	-	-
	Sprinkler								
S1	U(0.017, 0.064) (0.017-0.064) 10% (based on assumed floor area covered by a sprinkler system) of minimum and maximum found in Malm & Pettersson (2008).	0,1	1	1,2	0	1	-	-	-
	CO_2								
C1	T(0.28, 0.35, 0.42) (0.35 20/20) Both NK (1994) report and Zalosh et al. (1996) gives a number of 35% probability for total extinguishing of fire by CO_2 systems.	0,1	1	1,2	0	0	1	-	-
	Fire Fighting								
FF1	T(0.6, 0.8, 1) (0.8 25/25) Estimation on the probability of successful fire fighting effort based on the NK (1994) report and Zalosh et al. (1996).	0,1	1	1,2	0	0	0	1	-
	Safety								
SA_p1	1 If incident is not detected, there is no risk of fatalities	0,1	1	0	-	-	-	-	1

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Table E.4 Continuation from previous page

		Branch/-es							
	Distribution	Explosion	Fire	Detection	Portable	Sprinkler	CO_2	Fire Fighting	Cost
SA_p2	Pert(0.75, 0.96, 1)	1	1	1,2	1	-	-	-	1
	Probability of a minor damage if the fire is preceded by an explosion and extinguished by portable means.								
SA_p3	Pert(0.75, 0.96, 1)	1	1	1,2	0	1	-	-	1
	Probability of a minor damage if the fire is preceded by an explosion and extinguished by the sprinkler system.								
SA_p4	Pert(0.75, 0.94, 1)	1	1	1,2	0	0	1	-	1
	Probability of a minor damage if the fire is preceded by an explosion and extinguished by the CO_2 system.								
SA_p5	Pert(0.75, 0.92, 1)	1	1	1,2	0	0	0	1	1
	Probability of a minor damage if the fire is preceded by an explosion and extinguished by fire fighting.								
SA_p6	Pert(0.75, 0.9, 1)	1	1	1,2	0	0	0	0	1
	Probability of a minor damage in case of a total loss and where an explosion has occurred.								
SA_p7	Pert(0.75, 0.98, 1)	0	1	1,2	1	-	-	-	1
	Probability of a minor damage if the fire not initiated by an explosion and is extinguished by portable means.								
SA_p8	Pert(0.75, 0.98, 1)	0	1	1,2	0	1	-	-	1
	Probability of a minor damage if the fire not initiated by an explosion and is extinguished by the sprinkler system.								
SA_p9	Pert(0.75, 0.96, 1)	0	1	1,2	0	0	1	-	1
	Probability of a minor damage if the fire not initiated by an explosion and is extinguished by the CO_2 system.								
SA_p10	Pert(0.75, 0.94, 1)	0	1	1,2	0	0	0	1	1
	Probability of a minor damage if the fire not initiated by an explosion and is extinguished by fire fighting.								
SA_p11	Pert(0.75, 0.92, 1)	0	1	1,2	0	0	0	0	1
	Probability of a minor damage in case of a total loss if the fire is not initiated by an explosion.								
SA_p12	Pert(0.75, 1, 1)	1	0	-	-	-	-	-	1
	Probability of a minor damage if an explosion without a following fire has occurred.								
	Financial								
FI_p1	1	0,1	1	0	-	-	-	-	1
	If an incident is not detected, there is no possibility of a total loss.								
FI_p2	0	0,1	0,1	0,1,2	0	0	0	0	1
	If a fire is not extinguished by last fire fighting effort it is considered to be a total loss.								

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Table E.4 Continuation from previous page

		Branch/-es							
	Distribution	Explosion	Fire	Detection	Portable	Sprinkler	CO_2	Fire Fighting	Cost
FI_p3	1	0,1	1	1,2	1	-	-	-	1
	If a fire is extinguished by portable means there is no possibility of a total loss.								
FI_p4	1	0,1	1	1,2	0	1	-	-	1
	If a fire is extinguished by the sprinkler system the damage will be limited to a confined area and will not lead to total loss.								
FI_p5	1	1	0	-	-	-	-	-	1
	A single explosion is not believed able to cause a total loss.								
FI_p6	Pert(0.75, 0.98, 1)	1	1	1,2	0	0	1	-	1
	Probability of a minor damage if the fire is preceded by an explosion and extinguished by the CO_2 system.								
FI_p7	Pert(0.75, 0.94, 1)	1	1	1,2	0	0	0	1	1
	Probability of a minor damage if the fire is preceded by an explosion and extinguished by fire fighting.								
FI_p8	Pert(0.75, 1, 1)	0	1	1,2	0	0	1	-	1
	Probability of a minor damage if the fire not initiated by an explosion and is extinguished by the CO_2 system.								
FI_p9	Pert(0.75, 0.96, 1)	0	1	1,2	0	0	0	1	1
	Probability of a minor damage if the fire is not initiated by an explosion and is extinguished by fire fighting.								

Table E.5: Distribution table of costs of the events. Safety costs followed by Financial costs. For notations used for distributions and branch ID see Section 4.2. The distributions are motivated in Section 6.

		Branch/-es							
	Distribution	Explosion	Fire	Detection	Portable	Sprinkler	CO_2	Firefighting	Cost
	Safety								
SA$_c$1	0	0,1	1	0	-	-	-	-	1,2
	If fire is not detected there is no possibility of personal injuries.								
SA$_c$2	β(0.5, 25, 1, 25)	0,1	0,1	0,1,2	0,1	0,1	0,1	0,1	2
	Personal loss in case of a fatal incident.								
SA$_c$3	β(1, 50, 0, 1)	0,1	0,1	1,2	0,1	0,1	0,1	0,1	1
	Personal loss in case of a minor (non-fatal) incident.								
	Financial								
FI$_c$1	0.6×β(2.37, 13.53, 5,000,000, 300,000,000)	0,1	0,1	0,1,2	0,1	0,1	0,1	0,1	2
	Cost for a total loss, based on ship value.								
FI$_c$2	FI$_c$1	0,1	0,1	0,1,2	0	0	0	0	1
	If a fire is never extinguished the ship is lost, resulting in a total loss.								
FI$_c$3	Pert(5000, 20,000, 70,000)	0,1	0,1	0,1,2	0,1	0,1	0,1	1	1
	Income loss per day								
FI$_c$4	0	0,1	1	0	-	-	-	-	1
	Days laid off for repairs in cases where a fire is not detected.								
FI$_c$5	U(0, 20,000)	0,1	1	0	-	-	-	-	1
	Repair costs in cases where a fire is not detected.								
FI$_c$6	FI$_c$3×FI$_c$4+FIC 5	0,1	1	0	-	-	-	-	1
	Total minor cost in cases where a fire is not detected.								
FI$_c$7	β(1.1, 15.5, 0, 30)	0,1	1	1,2	0,1	0,1	-	-	1
	Days laid off for repairs in cases where a fire is extinguished by portable means or by the sprinkler system.								
FI$_c$8	U(2500, 25,000)	0,1	1	1,2	0,1	0,1	-	-	1
	Daily repair costs in cases where a fire the fire is extinguished by portable means or by the sprinkler system.								
FI$_c$9	FI$_c$3×FI$_c$7+ FI$_c$7×FI$_c$8	0,1	1	1,2	0,1	0,1	-	-	1
	Total minor cost in cases where a fire is extinguished by portable means or by the sprinkler system.								

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Table E.5 Continuation from previous page

		Branch/-es							
	Distribution	Explosion	Fire	Detection	Portable	Sprinkler	CO_2	Firefighting	Cost
FI_c10	$\beta(1.1, 5.5, 0, 180)$	0,1	1	1,2	0	0	1	-	1
	Days laid off for repairs in cases where a fire is extinguished by the CO_2 system.								
FI_c11	U(5000, 50,000)	0,1	1	1,2	0	0	1	-	1
	Daily repair costs in cases where a fire the fire is extinguished by the CO_2 system.								
FI_c12	$FI_c3 \times FI_c10 + FI_c10 \times FI_c11$	0,1	1	1,2	0	0	1	-	1
	Total minor cost in cases where a fire is extinguished by the CO_2 system.								
FI_c13	Pert(0, 22.5, 180)	0,1	1	1,2	0	0	0	1	1
	Days laid off for repairs in cases where a fire is extinguished by fire fighting.								
FI_c14	U(5000, 50,000)	0,1	1	1,2	0	0	0	1	1
	Daily repair costs in cases where a fire the fire is extinguished by fire fighting.								
FI_c15	$FI_c3 \times FI_c13 + FI_c13 \times FI_c14$	0,1	1	1,2	0	0	0	1	1
	Total minor cost in cases where a fire is extinguished by fire fighting.								
FI_c16	U(10,000, 1,000,000)	1	0	-	-	-	-	-	1
	Total minor cost in cases where an explosion that is not followed by a fire occurs.								

F Results

Table F.1: Results with a 90% confidence interval. Note that the values of minor and major can not be added to yield the total, these values are an average of all cases of minor and major values respectively only. The numbers do not account for the different probabilities for minor/major.

Result		Mean	Percentil			Unit
			5%	95%		
Incident Freq.		2.51	1.58	3.84	$\times10^{-3}$	incidents/shipyear
Probability/Frequency of Financial Loss						
Incident	Minor	0.88	0.82	0.94		-
	Major	0.12	0.06	0.18		-
Shipyear	Minor	2.21	1.39	3.40	$\times10^{-3}$	incidents/shipyear
	Major	0.30	0.13	0.53	$\times10^{-3}$	incidents/shipyear
Cost for Financial Loss						
Incident	Total	4.60	1.75	8.89	$\times10^{6}$	USD/incident
	Minor	0.95	0.27	1.98	$\times10^{6}$	USD/incident
	Major	29.16	9.22	57.98	$\times10^{6}$	USD/incident
Shipyear	Total	11.51	3.86	24.25	$\times10^{3}$	USD/shipyear
Probability/Frequency of Injuries/Fatalities						
Incident	Minor	0.93	0.90	0.96		-
	Major	0.07	0.04	0.10		-
Shipyear	Minor	2.33	1.47	3.58	$\times10^{-3}$	incidents/shipyear
	Major	0.17	0.09	0.30	$\times10^{-3}$	incidents/shipyear
Cost for Injuries/Fatalities						
Incident	Total	120.3	58.6	230.9	$\times10^{-3}$	lives/incident
	Minor	19.70	0.99	58.42	$\times10^{-3}$	lives/incident
	Major	1.48	1.00	2.86		fatalities/incident
Shipyear	Total	3.02	1.23	6.35	$\times10^{-4}$	lives/shipyear
Total loss per year for entire world fleet of oil tankers (2,526) and container vessels (2,520) built 1998 or later						
Frequency	Total	12.64	7.98	19.38		incidents/year
Safety	Total	1.52	0.62	3.21		lives/year
Financial	Total	58.10	19.48	122.38	$\times10^{6}$	USD/year

G Persons Consulted

Several persons have been consulted and interviewed throughout the work of the thesis for discussions on technical matters as well as issues involving the risk analysis process. A brief description of these verbal sources is listed below, including information on their background and in what areas they have contributed.

Busche, Christoph (Germanischer Lloyd) Department for Fleet in Service - Technical Support Statutory at GL. Was consulted on 18 August 2009 on regulations on fire extinguishing systems, and discussions on the systems in use within the current world fleet.

Ionel, Hincu (Chief Engineer Container Vessel) Engineer from Constanta Maritime University, Romania who has worked in the shipping industry since 1981. Was interviewed in July 2009 on his experience on machinery space fires: the most critical components, fire protection systems, safety routines on board and fire fighting training etc.

Kay, Alexander (Junge & Co) Insurance broker who was consulted over the phone on 16 September 2009 on insurance issues, such as premiums, insurance values of ships and owner's deductibles.

Kähler, Nina (Germanischer Lloyd) Strategic Research and Development Department at GL. Has been consulted mainly in the early stages of the thesis work for questions on ship construction and general enquiries on machinery space design.

Munzel, Martin (Scandinavian Underwriters Agency) Surveyor at SCUA who was interviewed on 20 August 2009 on financial costs of machinery fires. Supplied information on examples of actual repair costs after ship fires and provided information on the general consequences and different types of costs in relation to ship fires.

Pötzsch, Ingmar (Germanischer Lloyd) Deputy Head of Fleet Service Damage and Repair at GL. Has provided guidance throughout the thesis work on the GL Damage and GL Docu databases and other casualty data and has been consulted on potential risks leading to fires/explosions as well as machinery damages following such incidents.

Rüde, Erich (Mechanical Engineer, Germanischer Lloyd) Project engineer at the Strategic Research and Development Department at GL, working in shipping industry since 2006. Has been consulted throughout the work of the thesis for discussions on the FSA method as well as safety assessment and risk analysis issues.

Vosvolis, Athanasios (Alpha Marine Services) Was contacted via e-mail on 17 July 2009, and has provided various estimations on the financial costs of machinery space fires: costs with respect to restoring the fire protection systems, replacing machinery components, cleaning the machinery space. Also provided information on indirect costs for the shipping companies such as income losses during lay-up and repair and cost for normal operation of a cargo vessel.

Zalevski, Andrei (Second Officer Container Vessel) Officer training at Maritime College, has worked in shipping since 1987. Was interviewed in July 2009 to provide information on maritime fire safety from the crew perspective: fire fighting procedures, training, crew responsibilities, previous experience of machinery space fires etc.

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