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BBN Model with Quantitative Inputs for Risk Analysis of Uncontrolled Fire in Machinery Space

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Reliability, Availability, Maintainability and Safety (RAMS)
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Master Thesis

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Preface

This thesis report is written in culmination of two years master program (MSc) in Reliability, Availability, Maintainability and Safety (RAMS) within the department of Production and quality engineering at Norwegian University of Science and Technology (NTNU), Trondheim, Norway. Work on the topic of this report began in autumn 2015 in the specialization project and continued with the master thesis in spring of 2016.

This report suggests a Bayesian Belief Network (BBN) for risk analysis of uncontrolled fire in engine room of ships. The report includes review of literature, the suggested BBN model, quantification and discussion of the factors in the model and recommendation for further work.

This report is prepared in collaboration with the National Ship Risk Model (NSRM) Project, which financed, by Norwegian Maritime Directorate, Norwegian Coastal Administration (NCA) and Norwegian Research Council with the purpose of developing a comprehensive risk model for all the ships sailing in Norwegian waters. The NSRM project coordinated by NTNU, NTNU Social Research, SA and Safetec.

The intended readers of this report may need to be familiar with the terminologies and concepts in risk analysis. The basic knowledge in domain of Reliability and Bayesian Belief Network (BBN) is required to understand the quantification of factors and the suggested model in this report. Technical knowledge/experience in marine engineering (ship engineering) is recommended for better understanding of the risk influencing factors (RIF) and interrelation between them in the BBN model.

Trondheim

Hooshyar Azizpour

Acknowledgment

I would like to express my heartfelt gratitude to my supervisor Professor Stain Haugen for his great support, guidance and invaluable comments that without his help this report would never be complete.

Special thanks goes to the NSRM project team for giving me the honor of writing this report in collaboration with their project.

Sincere thanks to the RAMS group in department of Production and Quality Engineering at NTNU, for all their support, guidance and the knowledge that I gained through studying my master in RAMS.

H.A

Summery and conclusion

The past decades has witnessed a significant increase in the number and volume of international trade through the sea. Thousands of ships are sailing in the coastal and international waters all over the world. Accident in the sea transport not only results loss of property for the owners of vessels and traders of cargo, but also threatens the environment and the humans who are directly or indirectly associated with the marine industry. One of the most dangerous accidents in ships is fire and statistics has shown more than 50% of the fires in the ships has happened in the aft area of the ship (MEPC 2008). Engine room of the ships by nature is susceptible to fire due to enclosing numbers of ignition sources connected to the pipes and storage tanks containing flammable liquids. In light of the increasing demand for higher level of safety in maritime transport international regulation concerning safety has been upgraded. Frameworks, procedures and regulations concerning fire safety in ships reflected in SOLAS chapter II-2. The accident reports shows that despite of the innovation and preventive regulations and measures, still the risk/frequency of fire is not low enough to be negligible. The critic to the regulation enforced by IMO through chapter II-2 SOLAS is that the rules are achieved largely based on past experiences and assessment of finite set of serious accident scenarios (Mermiris, et al. 2012). Literature review showed there is lack of literature in developing a risk model that can incorporate all the human, organizational and technical factors associated with risk of fire in engine room, which can be used for further analysis and revision of procedures and regulation concerning fire in machinery space.

This report reviewed the statistical reports in the literature about source and frequency of fire in the ships with focus on engine room fire. The influencing factors associated with the risk of uncontrolled fire in engine room identified. The main source of uncontrolled fire presented to be combustion of released hydrocarbons in contact with the ignition sources. Sources of leakage in engine rom classified to two main separated compartments of Purifier Room and Engine Room area. Engine room area includes Main Engine, Diesel Generators, Boiler, Incinerator, and other piping and electrical sources.

The probability/frequency of all of the risk influencing factors determined using the relevant literatures. BBN model developed for uncontrolled fire in engine room. Influence of different factors on each other discussed and the most appropriate probabilities/frequencies selected for the model. As a part of the further work (in order to determine weights for factors in the model) a pairwise comparison method introduce which needs a degree of expert judgment. For the final step, a semi 'mechanistic' approach introduced for developing the conditional probability tables. Sensitivity analysis recommended for identification of the most critical factors that their change might have the highest influence on outcome of the model.

The advantage of the BBN model in this report is that the model includes the most significant technical, human and organizational factors, which are standard in most of the ships. This property of the suggested model makes is applicable for analysis of fire in engine room of any type of ship in any part of the world. The suggested method for quantification of the network, instead of just relying on either expert judgment or statistical data, introduced an approach, which uses combination of both method and gives result that is more realistic.

Content

Abbreviations

AHP: analytical Hierarchy Process
BBN: Bayesian Belief Network
CPT: conditional Probability Table
DAG: Directed Acyclic Graph
DNV: Det Norske Veritas
DH: Double Hull
DU: Dangerous Undetected
DWT: Dead Weight Tonnage
EDG: Emergency Diesel Generator
FTA: Fault Tree Analysis
FOC: Flag of Convenience
FP: Fire Protection
GISIS: Global Integrated Sipping Information System
GT: Gross Tonnage
HFO: Human and Organizational Factors
HSE: Health, Safety, Environment
IAEA: International Atomic Energy Agency
IACS: International association of Classification Societies
IMO: International Maritime Organization
LMIS: Lloyd’s Marine Information System
LMIU: Lloyd’s Maritime Intelligent Unit
LRFP: Lloyd’s Registry Fair play
MoU: Memoranda of Understanding
MCS: Mont Carlo Simulation
NMA: Norwegian Maritime Authority
NFPA: National Fire Protection Association
NSA: Norwegian Ship owner Association
OREDA: Offshore & Onshore Reliability Data
PSC: Port State Control
PFD: Probability of Failure on Demand
P&I: Protection and Indemnity
RBD: Reliability Block Diagram
RIF: Risk Influencing Factor
RIAC: Reliability Information Analysis Center
SFSEM: Ship Fire Safety Engineering Methodology
SAFE: Ship Onboard Fire Engineering
SOLAS: Safety of Life at Sea
SIF: Safety Instrument Function
STCW: Standard Training of Certification and Watch keeping
UMS: Un-Manned System

Chapter 1

Introduction

1.1: Background

More than 70 of the earth surface is covered by water and which connects seven continents together. This made human in the early 4th millennium BC think of exploring the world and later trading the goods through the sea. Since then the focus on marine transport increased and eventually revolutionized by the first introduction of diesel engines for use in ships in 1898. Nowadays more than 80% of the world merchandise trade by volume is transported by ships trough the sea which has made the shipping industry an important player in the world economy. Use of fossil fuels for propulsion of ships in one hand enabled the vessels to move faster and brought feasibility of running huge vessels and in the other hand created the potential of risk of fire in ships. I compare with land-based structures and industries, fire in ship can be more dangerous because the help from outside in the form of fire brigade can hardly be replied on. Often the accommodation is constructed on just above engine room. Therefore, fire in the engine room not only causes loss of the control or immobilization of the ship, which might result in grounding and collision, but also threatens the passengers and staff who live in the accommodation. Study of accident data for crude oil tankers between 1980 to 2007 by Denmark maritime authority in form of formal safety assessment (FSA) on crude oil tankers (MEPC 2008) which submitted to International Maritime Organization (IMO), showed that, out of all reported fires, in the open sea area, 94% of fires started in the aft area of the ships. While in the terminals 84% of the fires happened in the aft area. The critical review of accident on AFRAMAX tankers accident (1978 to 2004) showed that 2/3 of all reported fires in the ships initiated in the machinery space (Papanikolaou , Eliopoulou og Alissafaki , et al. 2005). According to the analysis of fire accident reports, machinery spaces are naturally the most susceptible area to serious fire in compare with the other shipboard compartments (IMCA 2003). All the ships are subject to rules and regulation that established by IMO and enforced by flag states and classification societies. Concerning the fire hazard, Maritime Safety committee of IMO has the dominant legislation authority which issues the necessary requirements and the guidelines in Safety Of Life At Sea (SOLAS) document. All the requirements related to the safety, prevention and extinguishing the fire in the machinery space are documented in chapter II-2 of SOLAS. To increase the safety of ships regarding fire, sets of new regulations amended to SOLAS chapter II-2 and all the new amendments enforce from July 2002. Basically, the requirements in SOLAS are the minimum of requirements. Meaning that flag states and classification societies are allowed to set higher standards for the vessels that are registered with them. Now it comes into question that whether or not the current regulations and statistical figures of risk fulfill our standard and expectation. What are the significant factors that influence the risk. What measures needs to be adapted in order to improve the current safety level. In the past years presenting a risk picture in marine sector has been traditionally based on historical for the serious accidents (Montewka, et al. 2014). Due to low quality and under reporting in many cases it is hard to estimate the current exposure data for risk in different scenarios. In order to adapt a proactive approach for picturing the risk in marine sector, International Maritime Organization (IMO) introduced the Formal Safety Assessment (FSA) in 2002, which has not hitherto gained the considerable widespread application. The need of having a general risk picture for better understanding and analysis of factors that influence the risk of maritime transport in the Norwegian waters founded the main objectives of a project called National Ship Risk Model (NSRM) with the cooperation of Norwegian Maritime Authority (NMA), Norwegian Coastal Administration (NCA) and Norwegian University of Science and Technology (NTNU). Uncontrolled fire in engine room defined as one of the major threats for vessels. Bayesian Belief Network (BBN) suggested for risk modeling of factors that influence the uncontrolled fire in machinery space of vessels.

In collaboration with the NSRM project, the preliminary version of the BBN model for uncontrolled fire in engine room suggested and discussed qualitatively in the specialization project (TPK4550) in autumn 2015. As a further work in this master thesis (Reliability, Availability, Maintainability and Safety-RAMS master thesis-TPK4950), the aforementioned model developed, simplified, all the factors quantified and a methodology for developing the Conditional Probability Tables (CPT) suggested for further work.

The suggested model incorporate human, organizational and technical factors that are associated with the risk of fire in the engine room of vessels. The result of this report can be used as a part of the final report of NSRM project. Because fire in engine room of the vessels is independent of the position of ships, this model can be used for analysis of fire in engine room in any region of the world. For risk analysis of fire in a specific region, the statistical Automated Identification System (AIS) data about mean percentage of different type of ships in the specified region needs to be inserted into the model by changing the status of type of ship from decision node to chance node (See section 5.2).

1.2: Objectives

- Modify and simplify the preliminary version of the model and adjusting it with the data.
- Find the possible indicators and the probability of each factor according to the literature (if available)
- Discussing the suitability of data for quantification of the model according to interrelation between factors.
- Finding methods or potential sources of information for weighting the factors in the BBN model.
- Finding the method/information that helps determining the influence of factors on each other in order to develop the conditional probability tables.

1.3: Limitations

This thesis focused on the modeling the risk of uncontrolled fire in engine room of ships during normal operation in ports or at sea. Risk of fire during construction or maintenance in the yard is not considered.

The design, type and number of auxiliary machinery and fire protection barriers may vary in different type of ships. For instance, type and number of active firefighting barriers may vary in Liquid Natural Gas (LNG) carriers in compare with general cargo carrier. In this study, a generic design of engine room considered for identifying the risk influencing factors in the suggested BBN model.

Regarding the size of the ships, the assumption was a generic ship with a typical engine room, which is built in compliance with international regulations with having the capacity of non-limited voyage across the oceans.

The focus of BBN network in this thesis is initiation of fire in the engine room due to internal sources of ignition and other external sources of ignition like sabotage, lighting or initiation of fire in the other compartments such as pump room or accommodation did not considered in this report.

Data collection is always challenging Scope of survey for determining data for assigning the probability/frequency to the risk influencing factors in the model constrained to the published data in the literatures. Due to limited access to databases, database analysis did not carried out.

The assigned probability/frequency to some of the factors in the literature survey varied significantly, therefore the most suitable figures adapted for the model although the other results were credible as well.

Gathering team of expert for the expert judgment within the time limit of this thesis was a challenge. The methodology for weighting the factors and developing the conditional probability tables presented. The process of determining the weights suggested as the further work.

1.4: Approach

Topic of this thesis was the continuation of the specialization project. The preliminary model of BBN for fire in engine room adapted from the specialization report. In this thesis, the statistical report on fire in ships reviewed in the literature and all the factors in the model quantified according to the literature survey. The model modified according to data and the suitability of data for the model disused. The method of weighting the factors and developing the conditional probability tables presented for the further work.

The flow chart in figure 1.1 presents the flow of work in this report.

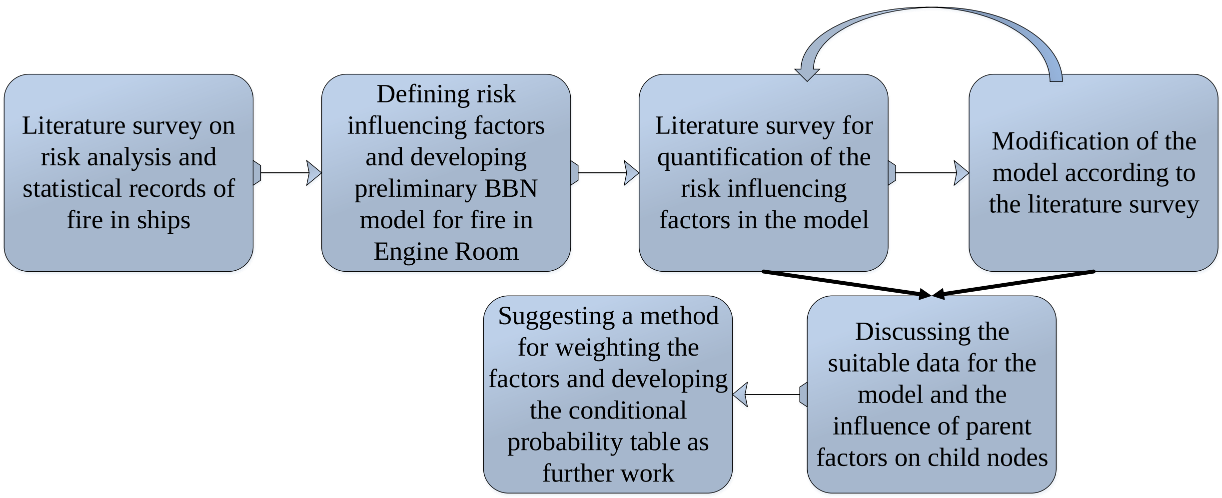


Figure 1.1: Flow chart of approach in writing the report

1.5: Description of the report

- Chapter 1: Introduction and background information, objective and limitation.
- Chapter 2: This chapter begins with review and comparison of statistical records on fire accidents onboard according to different published articles and reviews the previous studies in analysis of fire in engine room.
- Chapter 3: Quantification of different risk influencing factors (RIF) in the model according to the relevant published literatures presented in this chapter.
- Chapter 4: Introduction and summery of BBN is presented in this chapter.
- Chapter 5: The modified version of BBN presented and influence of factors on each other and the suitable data for quantification of each factor according to chapter 3 discussed.
- Chapter 6: summery of the report
- Chapter 7: presents methodology for weighting the factors and a semi ‘mechanistic’ methodology for developing the conditional probability tables.

Chapter 2

Records and researches on ship fire

In maritime industry and especially in shipping, different hazards may lead to accident if they cannot be controlled. In a broad categorization, we can divide them to four categories. Collision, Grounding, Fire and Foundering are the most known ones. Fire in ship and specifically, fire in engine room, in most of the severe cases leads to immobilization of the ship. Loss of propulsion power or steering control due to fire, leads to collision or grounding in case of being in the collision or grounding direction. Therefore, fire is one of the most hazardous accident in the ship. The first part of this chapter surveys the published statistical records of ship fire in the literature and the second part reviews the articles which adapted risk analysis approach to evaluate the risk of fire accident on board of ships.

2.1: Statistical reports on ships fire and fire in engine room

Many of the marine associated organizations have started to collect data in marine incident including fire. Based on accident databases numbers of reports have been published in analysis of recorded accidents.

In 1995 a survey report published by U.S. Department of Transportation. In this report fire and explosion casualty data analyzed in worldwide merchant vessels to determine the contribution of accidents to the marine pollution problem. The report used Lloyd's Casualty Information System Database in the period of 1978-1992. In 15 years period of observation 2370 fire/explosion accident reported. Freighters and Tankers had the highest frequency of accident by 42% and 32% respectively.

Figure 2.1 shows the distribution of fire accidents among different type of vessels in 15 years study period.

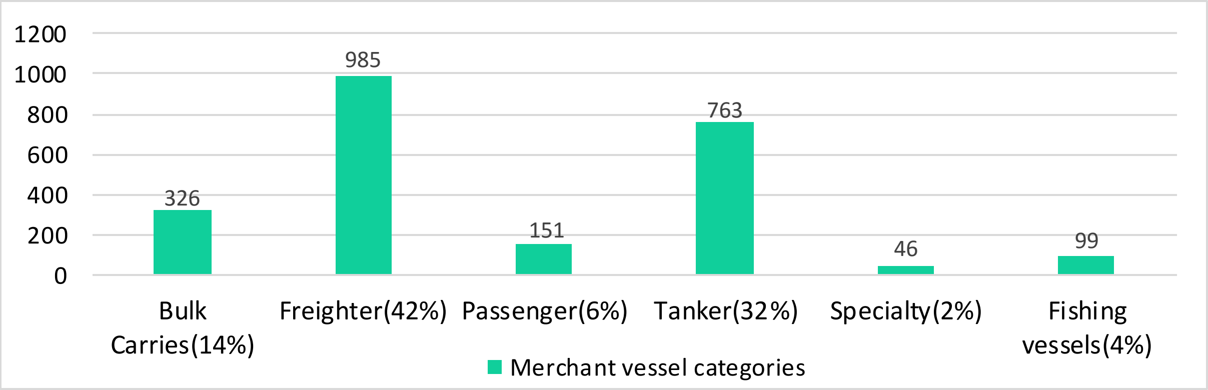


Figure 2.1: Distribution of fire/explosion accident in merchant vessel categories based on Lloyd's database 1978-1992 (Gentile and Dickenson 1995)

If we use the mean population of each vessel category to normalize the percentages in the report, Passenger ships with population of 376 vessels gets the frequency of Fire/Explosion was 2.7% per ship year (s-y) in Passenger ships during 15 years period. This normalized percentage was 0.9% per ship-year for Tankers with 5530 vessels in their fleet population. Freighters with the population of 13391 vessels experienced only 0.5% fire/explosion per ship-year accident in their fleet. This normalized percentage of fire/explosion accident for Bulk Carriers with 5230 vessels in their fleet was just 0.4% per ship-year in the fleet during 15 years period of study. In the normalization of data, vessels with the Gross Tonnage (GT) more than 1000 GT taken into account. That is the reason why the other vessel types such as Specialty or fishing vessels did not considered for normalization. Considering the ships with over 1000 GT (Tankers, Bulk carriers, Passenger ships, Freighters) we get on average the frequency of 0.006048 fire/explosion per ship-year, which is equivalent to the number of one fire in each 165.35 years per ship.

In many of the reports, occurrence of fire is normalized and presented in form of a frequency, rather than a percentage. For instance, in one of the reports by Det Norske Veritas (DNV) incident frequencies calculated for vessels, to and from the port of Prince Robert. The result showed that frequency of fire/explosion was not dependent on local factors such as traffic or weather. Therefore, the world wide average data took into account without any adjustment factor. Analysis of 10 years (2000 to 2010) statistical accident data from Lloyd’s Register Fairplay database, World Fleet Statistics and International Tanker Owners Pollution Federation Ltd by (DNV, Navigational Risk Assessment Report 2012) showed that the total frequency of fire/explosion per ship was once every 169 years. If we compare the calculated frequency of fire from Lloyd's Register Fairplay database (2000 to 2010) with the calculated frequency from accident Lloyd's data 1978-1992,(which was 165.35 ship-years) the result shows that over the time frequency of fire per ship year has not decreased significantly.

More study on Tankers accident reports in the database showed that among 763 accidents in tankers, majority of fires occurred when ships were on voyage. The figure 2.2 shows the distribution of ship status during occurrence of fire, based on report by (Gentile and Dickenson 1995)

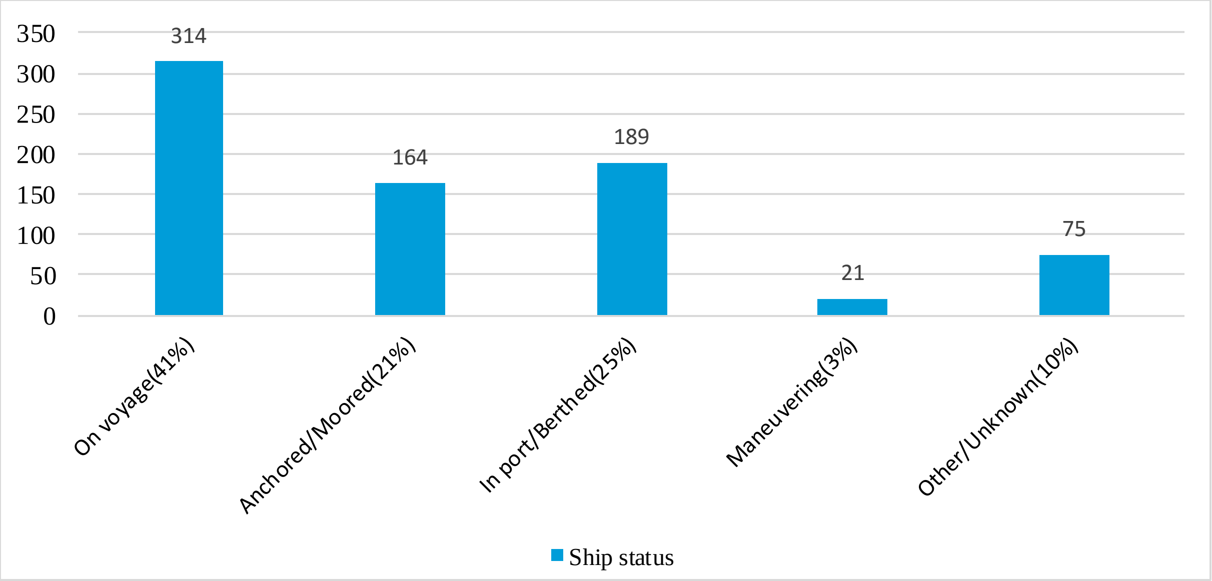


Figure 2.2: Ship navigation status of tankers based on Lloyd's Data (1978-1992)(Gentile and Dickenson 1995)

This report shows that out of 763 reported accidents in tankers, 371 of them was fire/explosion in the engine room, which represents approximately half of the accidents. Figure 2.3 illustrates the distribution of location of the reported fires in database.

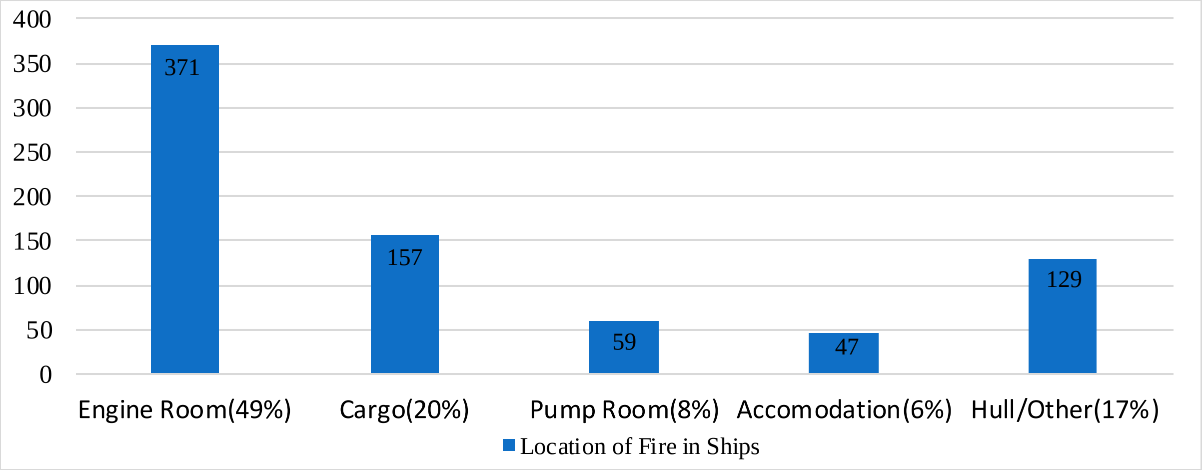


Figure 2.3: Location of Fire in Ships based on Lloyd's Data (1978-1992) (Gentile and Dickenson 1995)

Out of 371 accident in Engine Room, 191 accident (51.5% of accidents in engine room) reported to be serious. Distribution of the serious fire in engine room shows that Boiler and Main Engine were more associated with initiating of fire in compare with the other machineries (Gentile and Dickenson 1995). Figure 2.4 illustrates the distribution of fire in engine room.

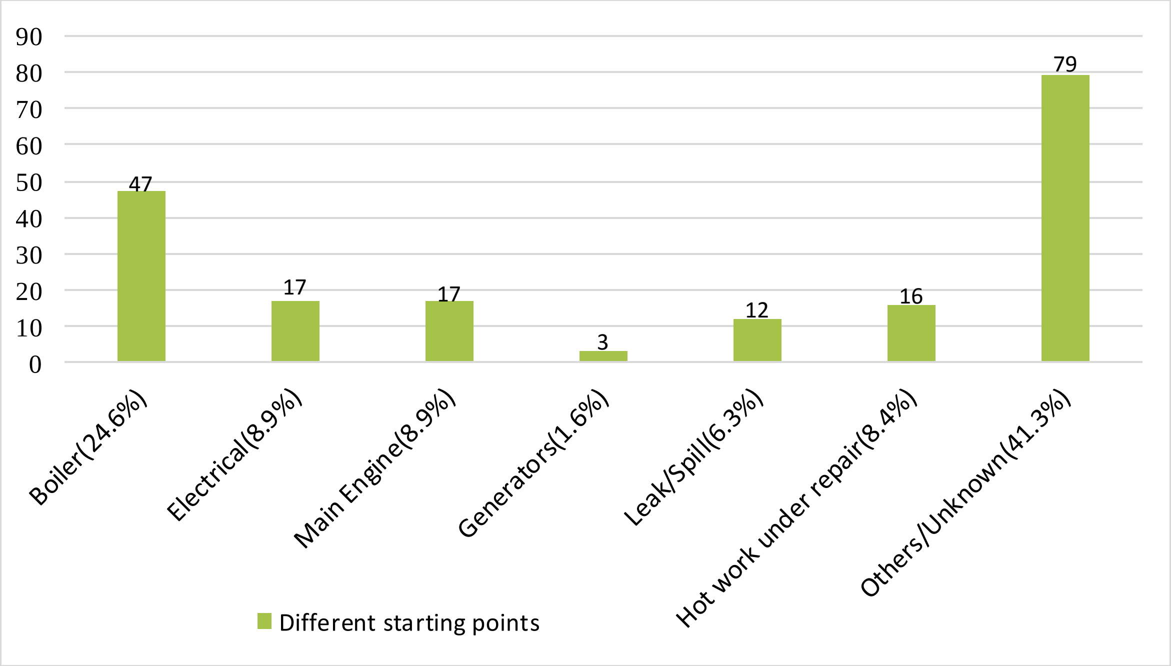


Figure 2.4: Distribution of serious fire incidents in tanker's engine room machineries Lloyd's data(1978-1992) (Gentile and Dickenson 1995)

Critical review of Aframax tankers accident based on analysis of reported accidents during 25 years according to database in Lloyd's Marine Information Service (LMIS) from 1978 to early 2004 published by (Papanikolaou , Eliopoulou and Alissafaki , et al. 2005). In this article, great majority of sources of fire reported to be *Internal Sources* by 97% and just 3% of *External Sources* caused fire. In the incidents that fire was caused by *Internal Sources*, 83% of them took place in the ship's aft area (which is equivalent to 80% of total accidents), 16% in cargo/slop tank and 1% in ballast tanks/void space. Figure 2.5 shows the distribution of fire in the reported database.

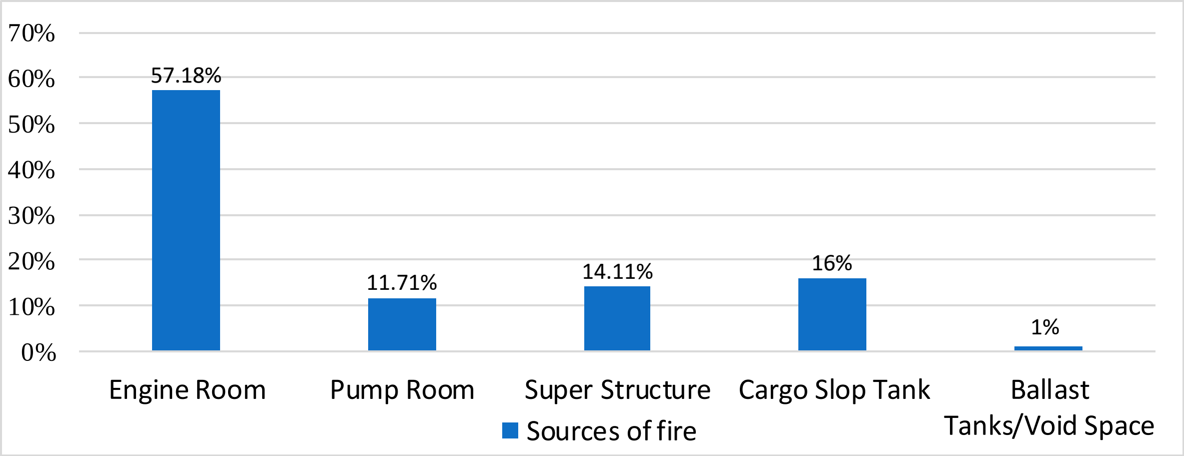


Figure 2.5: Distribution of fire in ship with internal source in LMIS (Papanikolaou, et al. 2005)

This result confirms the findings of report by (Gentile and Dickenson 1995) in figure 2.3 which shows about the half of fire accident in ship occurs in the engine room. Both studies used the same database but the later one analyzed a wider time span.

In the study of worldwide tankers accidents, frequency of fire/explosion calculated based on Lloyds Register Fairplay database (LRFP-2007) and presented to be 0.00241 per ship year (Brandsæter and Hoffmann 2010).

The statistical result in this report for Aframax tankers shows that 39% of fires in engine room had a serious degree of severity, 3% resulted in total loss of the ship and the rest 58% of incidents had no serious degree of severity.

At the time of fire incident in engine room 72% of the Aframax tankers in this study were in voyage, 12% in Berth, 12% during discharge or Bunkering and the rest 4% took place when the vessels were under repair (Papanikolaou , Eliopoulou and Alissafaki , et al. 2005)

“Machinery spaces are, by their nature, are the most susceptible of all shipboard compartments to serious fire” (IMCA 2003).According to this statement analysis of 165 fire reports in DNV database from 1992 to 1997 by (Det Norske Veritas 2000) showed that two third of fire breakouts in ship starts from engine room. They also reported that 56% of all fire breakouts in engine room initiated by leakages of oil/hydrocarbons onto hot surfaces.

One of the practical methods of finding the frequencies of occurrence of accidents is to look at databases of accident reports. Depend on the method of collecting the data for database, the limitations, geographical region of collecting the data and the degree of underreporting; the outcome frequency from analysis of data might vary. Therefore, all accident data needs normalization.

Similar to the aforementioned reports from data analysis, NTNU Social Research published a report of statistical analysis of Norwegian Maritime Authority (NMA) incident database. This research used statistical incident report data for almost 33 years from 1981 to 2014. During this period 614 accident out of 5997 recorded accidents reported to be fire/explosion. Result shows some similarities and dissimilarities with the statistical report by U.S Department of Transportation (Gentile and Dickenson 1995).

Both two reports clearly show that majority of fire incidents reported when ships were in voyage and minority of them reported during maneuvering (Figure 2.6).

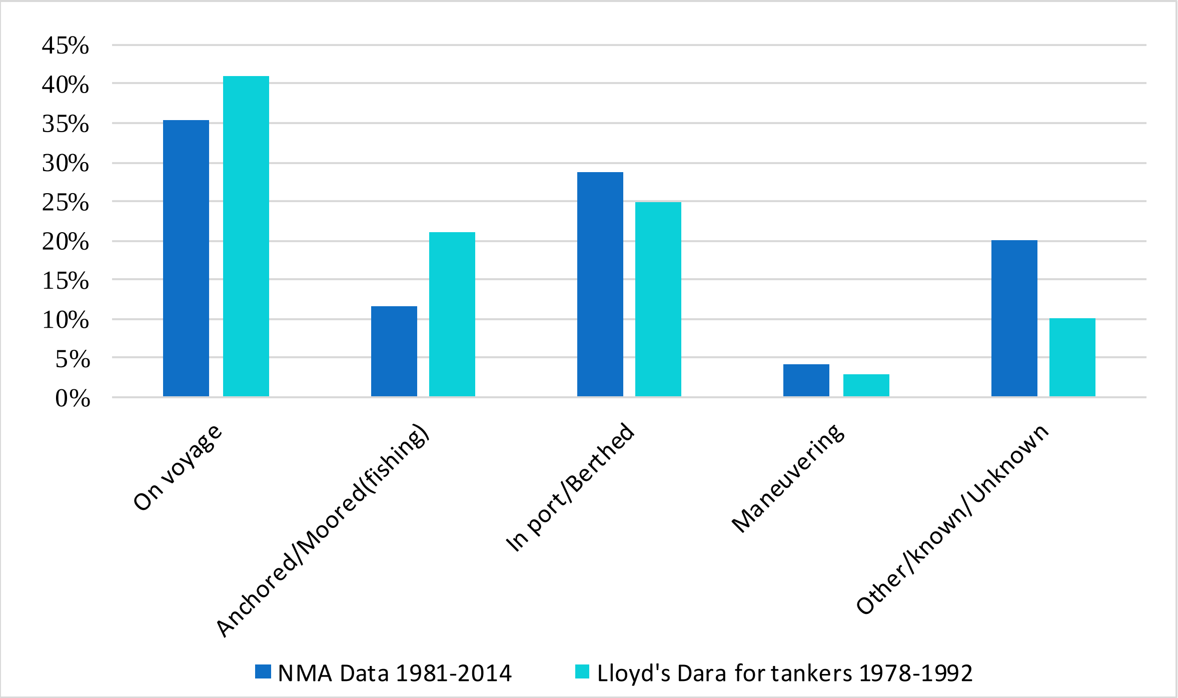


Figure 2.6: Comparison of Lloyd's data with NMA data

The statistical data in NMA database showed that fire incident reported more in old ships with age of more than 25 years. (Note: the figures are not normalized with the total number of ships under observation. The high percentage of fire in old ships might be due to high number of old ships in the Norwegian waters) Figure 2.7 presents the distribution of fire accident corresponding with ship age group (Stornes 2015).

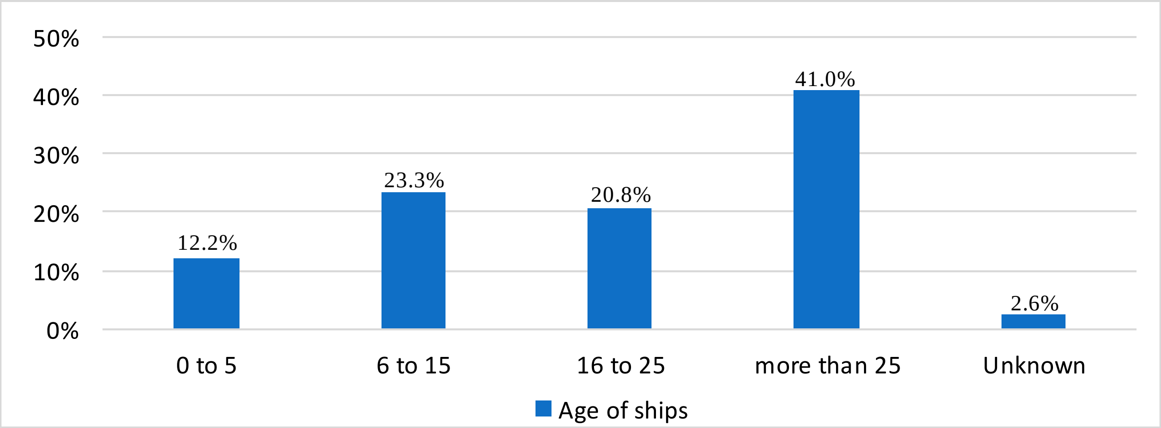


Figure 2.7: Distribution of age of ships in fire incidents in NMA Data 1981-2014 (Stornes 2015)

There is always degree of difference in results of statistical analysis of data between two different databases. Therefore, there is a need for normalization of data; otherwise, the percentages cannot give the accurate estimation of frequencies. This can be due to many factors such as the region that data is collected (impact of the local industries), or the period that data is collected, etc. For example, fishing industry is widespread in Norwegian waters and density of number of fishing vessels per squared kilometer in Norwegian waters is high. Due to this face, percentage of fire accidents reported in fishing vessels in NMA database was 64.8%, much higher than reported fire in fishing vessels based on Lloyd's database, which just included 4% of all fire incidents. Figure 1.7 shows the distinct variation in the two databases.

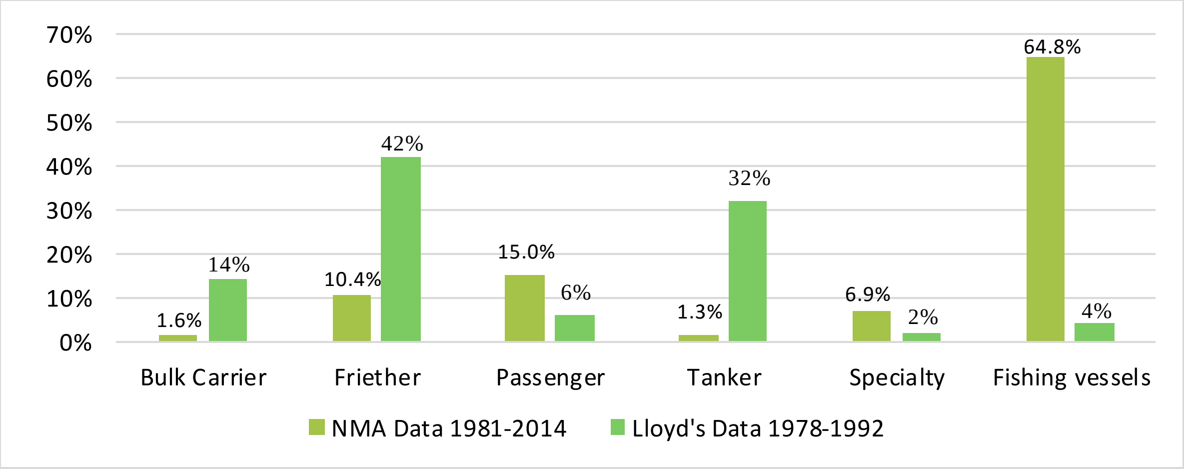


Figure 2.8: Comparison of Fire/Explosion accidents in ship type

Finding a source of reliable data is essential for qualitative and quantitative analysis in risk assessment. As discussed earlier depend on the source of data the statistical results might vary in some cases. Typically, accident statistics on generic vessels can be obtained from historical data from the sources such as data collected by government agencies, classification societies, insurance companies and Protection and Indemnity (P&I) Clubs. In some cases, a degree of judgment estimated by experts is considered specifically when lack of reliable data is significant. As discussed earlier, analysis different databases might give rather different results for frequency of an accident such as fire. Further records of frequency of fire, according to the analysis of different databases are presented in the following tables.

Table 2.1 presents the calculated frequency of fire per ship type according to the recorded accident data from DNV database (1992 - 2004), which included 300 fire accident reports for more than 2500 ship-years.

Table 2.1: Fire frequency per ship type according to DNV data (1992-2004) (Nilsen 2007)

Ship Type	**Fire frequency per ship-year**
Whole DNV fleet, 4300 vessels	7×10^{-3}
Oil carriers	2×10^{-3}
Fishing vessels	2×10^{-3}
Supply vessels	2×10^{-3}
Dry cargo	3×10^{-3}
OBO (Ore / Bulk / Oil)	4×10^{-3}
Bulk	4×10^{-3}
Chemical carrier	6×10^{-3}
RoRo, container	7×10^{-3}
Gas carrier	7×10^{-3}
Passenger	1.6×10^{-2}

According to the report from DNV accident database, the majority of fires reported to occur in engine room (table 2.2).

Table 2.2: Origin of fire according to DNV statistics (1992-2004) (Nilsen 2007)

Origin of fire	**Number (%)**	**Fire frequency per ship-year**
Engine room	63	4.4×10^{-3}
Accommodation	10	7.0×10^{-4}
Cargo area	27	1.9×10^{-3}

Study of accident data for passenger ships in IMO Global Integrated Shipping Information System (GISIS) for fire accidents showed that engine room was more prune to fire in passenger ships. Table 2.3 presents the frequency of fire in passenger ships according to IMO-GISIS (1998-2007).

Table 2.3: origin of fie in passenger ships (IMO-GISIS 1998-2007) (Karhula 2008)

Origin of the fire	**Fire frequency per ship-year**
Machinery Space	9.3×10^{-4}
Accommodation	1.4×10^{-4}
Cargo spaces	2.0×10^{-4}
All spaces	1.3×10^{-3}

2.2: Literature review for risk modeling of fire

One of the earliest attempts in developing a risk model for fire made by Nelson(1972) who suggested a method to evaluate relative levels of fire risk in building (Goal Oriented System Approach to Building Fire Safety). The method further adapted and developed by Richards and Fitzgerald (1984) and they suggested Ships Fire Safety Engineering Method base on the engineering method for Building Fire Safety (Nelson-1972). Ship Fire Safety Engineering Method for the first time used by Richards-1987 to evaluate the risk of different levels of fire in preliminary design of Polar Icebreaker Replacement for U.S. Coast Guard. (Sprague, Richards and Blanchard 1992). The objective of the aforementioned method was to provide a comprehensive model for analysis of ships fire safety, which can be applicable for all types of ship all over the world. Concept of the method was determination of the relative safety and vulnerability of ship in case of fire on the basis of compartment-by-compartment. In this method, flame movement introduced as the central component in fire safety analysis. The method distinguished between incipient fire and established burning which considered occurrence of a flame with approximately 10 inches of height.

The most appropriate time for application of this method is during the preliminary design phase of ship. The method was fundamentally a probabilistic-based fire risk analysis methodology and the probability of limiting spread of flame determined in a comprehensive structured framework utilizing network diagrams.

Ship Fire Safety Engineering Methodology (SFSEM) took into account all relevant aspects of fire safety such as growth and spread rate of fire and effectiveness of passive and active barriers. Ship Applied Fire Engineering (SAFE) is a computer program that implements the Ship Fire Safety Engineering Methodology (SFSEM) to evaluate probability of failure in spaces and barriers limiting the fire in ship. SAFE program also calculates the most probable path of fire spread for specific time duration. A Methodology for Evaluation of Ships Fire Safety published by (Sprague, Richards and Blanchard 1992) which gives comprehensive overview about using SFSEM. Later, the complete report about theoretical basis of the SFSEM published by U.S Coast Guard Research Development Center (Sprague and Dolph 1996).At the same time in 1996 the aforementioned software program (SAFE) developed by U.S Coast Guard Research and Development Center that implements SFSEM.

BBN, as a strong tool for analysis of probabilistic models has been used in many of publication to model risk of fire in different prospects. In the following the relevant studies reviewed.

Modeling of fire spread in buildings by Bayesian network (Cheng and Hadjisophocleous 2009) is one of the articles, which presents a model to estimate the probability of spread of fire from one compartment to the other compartment by using BBN. Further, in this study two different scenarios modeled. Spread of fire in building without working of sprinkler system or with sprinkler system working and the results compared. The result showed that sprinkler system as a barrier has significant effect on reduction in the speed of growth of fire. Concluded that probability of spread of fire is dependent to the probability of failure of barrier (Cheng and Hadjisophocleous 2009).

Risk of human fatality in building fire, a decision tool using Bayesian network by (Hanea and Ale 2009) was another study to estimate total risk for human fatality in case of uncontrolled fire. In this study all the factors that contributed in a risk of human fatality, like behavior of human and fire fighters during evacuation, structure of building, characteristics of building and environment took into consideration in a general model that can be applied in most of the new building in the Netherland (Hanea and Ale 2009).

In another study base on the previous study by (Hanea and Ale 2009), the same probabilistic model suggested use of Bayesian network to analysis the percentage of death in Schiphol Cell Complex fire (Hanea, Jagtman and Ale 2012).

A dynamic Bayesian network for modeling of evacuation time during fire was another study that focused on building a model with BBN, which can be used to analysis the most influential factors in estimation of time of evacuation in case of fire in ship (Sarshar and Radianti 2013).

In one research coordinated by IMO Fire and Safety committee. Based on the statistical data, the main sources and frequencies of fire in engine room identified and reported. In this study, 6000 ships for a period of 13-year-long were under observation and 73 fire accident from this sample group took into consideration for identification of main cause of fire and calculation of the frequencies. The study showed that fire in engine room contributed about, in overall 30-50% of the fires in the ships. Out of this percentage 60% of the fires in the engine room caused by break out of leakage in the fuel oil and diesel oil system. Vibration identified as a main contributor to the occurrence of leakage and couple of risk reducing measures recommended in this paper. At the end the effectiveness of suggested risk reducing measures confirmed by sensitivity analysis of the factors in the Bayesian Belief (BBN) model (Charchalis and Czyz 2011).

Ship's Engine Room Fire Modeling is the title of an article, which used special software program called CFAST (Consolidated Model of Fire and Smoke Transport), to estimate the rate of heat transfer and growth of fire in the engine room assuming that fire starts in the main engine area with crank case explosion. The analysis carried out with assuming having a model of a concrete engine room, which divided to 9 compartments in half-side cross section of engine room. The analysis carried out with the assumption that, air supply system worked which contributed to the spread of smoke and heat in the engine room (Stojan Petelin 2003).

Upon further searches in the published articles regarding any track of research in suggesting a model for analysis of uncontrolled fire in the ships engine room, almost no study was published in this field. The only article, which was published in field of analysis of consequences of fire in the engine room with use of BBN was written by (Jia Jia 2013).

In this article, a risk assessment model recommended for analysis of fire in naval ships. Assuming that ship was in a mission in the war and was subject to attack by missile, from an external source such as another war ship or aircraft. Therefore, the main reason of fire was an external attack (Non-contact Explosion) and not a failure or ignition in the ship. In this article, the whole ship divided to 5 compartment along the length of the navy ship and a method proposed to assess the degradation of each compartment when fire starts in the result of non-contact explosion (external attack). In this model, an estimation of risk for each specified compartment evaluated and the total risk for ship in consequence of fire caused by non-contact explosion (external attack) during a war mission calculated by the use of BBN (Jia Jia 2013).

Chapter 3

Quantification of the factors influencing risk of fire

IMO recognized that fuel oil, lubricating oil and other flammable lubricating oil system are the major sources of fire onboard on ships. There are also many potential ignition sources in a machinery space such as hot surfaces e.g. exhaust pipes and steam pipes (Tarelko 2012). Fire safety regulation including Safety of Life At Sea (SOLAS) introduced by International Marine Organization (IMO) safety committee. IMO enforced regulation that improves the safety of ship and staff through SOLAS, which includes regulations concerning fire safety as well. The regulation enforced by SOLAS criticized for couple of reasons. For instance, the enforced regulation by SOLAS are based on prescribing design and performance based approaches. The weakness of this methodology is twofold: first, it does not provide systematic framework for testing fire scenarios. Second, it might be too rigid to accommodate new design (Lohrmann , Kar and Breuillard 2011)

Developing and analysis of a risk-based probabilistic model for fire safety in ship's engine room can help better understanding of the different factors that can influence frequency of fire in ship. Result of the analysis can be used to implement risk-reducing measures in order to meet the desired risk/frequency of fire according to the risk acceptance criteria.

This chapter presents the most common type of fire in the engine room and introduces the influencing factors that contributes to developing an uncontrolled fire in engine room. Literature survey used for quantification of the suggested factors, which will be used in developing Bayesian Belief Network for risk analysis of uncontrolled fire later in this report.

3.1: Fires:

Leakage or release of flammable materials can lead to fire that triggers by number of potential ignition sources such as spark, open flame, hot surface (Hot spot) etc. Depending on the type of release scenarios in the marine/offshore environment, fires are classified mainly into four types:

Pool Fire, Jet Fire, Fire Ball and Flash Fire (PULA, et al. 2006).In the engine room fire scenarios, pool fire is the most likely fire to happen. Description of pool fire comes in the following.

3.1.1: Pool fire:

Pool fire is a turbulent diffusion fire that is burning above a pool of vaporizing hydrocarbons where the momentum of fuel vapor is negligible. There is a high probability of occurring pool fire in marine and offshore environment specifically in ship's engine room and offshore platforms due to continues handling of heavy hydrocarbons onboard. Sources of release of fuel can be overfilling of storage tanks by accidentally, breakdown of flanges or connections, rupture of pipes tanks etc. The released hydrocarbon forms a pool on the surface and upon the ignition results in a pool fire (Pula, et al. 2005).

3.2: Introducing and quantification of Risk Influencing Factors (RIF) associated with uncontrolled fire using literature survey

In all risk assessment methods, identification of Risk Influencing Factors (RIF) is one of the basic steps through analysis. Depending on the accident scenario in the analysis, RIFs can be associated with Human and Organizational Factors (HOF) or technical factors. In order to quantify the RIFs, different approaches are adapted according to the essence and definition of each RIF. When it comes to Human and Organizational involved factors, method of quantification can be expert judgment, analysis of human response to the questionnaires or statistical analysis of accident scenarios which the root causes are identified to be HOFs. In the risk models, some of the RIF are associated with the technical factors. On order to quantify the technical RIFs, generic reliability data from sources like OREDA can be considered. In many cases due to the complexity of tasks or functions, evaluation of Probability/Frequency of one factor needs modeling the interrelation between root causes/elements which have influence on the status of the corresponding RIF. In many cases relation of RIF and the root causes can be modeled with Fault Tree Analysis (FTA).

In the application of Bayesian Believe Network (BBN), the quantified RIFs can be discrete or continues which the discrete domain is usually finite (Kjaerulff 2008). The variable of RIF in the BBN can be presented in the form of any discrete status such as "True or False", "Yes or No", "High, Medium or Low", "any figure" or continues such as "0 to 5", $(-\infty, 0]$,etc.

For analysis of any scenario based on the three main categories of Human, Organization and Technical factors, all the factors that may contribute directly or indirectly in the outcome of scenario need to be identified. Table 3.21 presents the risk Influencing Factors (RIF) involved in analysis of uncontrolled fire in the ship's engine room using BBN.

Table 3.1: List of risk influencing factors in suggested BBN for uncontrolled fire in Engine Room

ID	Name of Node	ID	Name of Node
1	Maintenance/Inspection Efficiency	13	High expansion foam system fail to suppress fire
2	Deficient training	14	Failure of fire damper
3	Ship class registry	15	Emergency fire pump fail to supply water
4	Insufficient Emergency Plan	16	Probability of detection of fire
5	Ship comply with new regulation	17	Quick closing valves close on demand
6	Ships flag	18	Ship in sailing/stop
7	Proper action on time	19	Type of ship
8	Not Comply with instruction	20	Undetected leakage in purifier room
9	Safety culture	21	Undetected leakage in engine room area
10	Manual suppression fail to control fire	22	Probability of having ignition
11	Age of ship	23	Starting a fire
12	Hyper mist system failure	24	Developed uncontrolled fire(outcome scenario in the BBN model)

In order to quantify the suggested factors in BBN model for uncontrolled fire, literature survey carried out to investigate the estimated probabilities of the identified risk influencing factors in table 3.1.

3.2.1: Maintenance/ inspection efficiency (1):

Maintenance of ship is one of the most critical factors that influences the reliability of equipment in the ship. One of the measures for quantification of ship maintenance is the amount of budget that spends for maintenance of ship. Obviously, the maintenance cost depends on the age, type and size of the ship. When the ship is new (Under 5 years old), many of the machinery are under guarantee and repair/replace of them, does not cost for the owner company. Therefore, the age of ship has to be taken into consideration when evaluating the maintenance efficiency.

The estimation of ship's maintenance and repair cost extrapolated from Drewry's ten year average daily cost for different vessel size and types from 2001 to 2010 presented in an article by (Li, Yin and Bang, et al. 2014).

In table 3.2, the maintenance cost of ships presented according to type and age of the ships. Range of cost in each column depends on the size of ship. (All the costs presented in (USD/year)) (Li, Yin and Bang, et al. 2014)

Table 3.2: Estimation of yearly maintenance cost according to ship type and size (Li, et al. 2014)

Ship type \ Age	**New(0-5 year)**	**Average(6-10 year)**	**Old(Over 10 year)**
Bulk	200,175 to 319,650	440,385 to 703,230	447,057 to 713,885
Tanker	383,775 to 580,650	844,305 to 1,277,430	857,097 to 1,296,785
Container	168,510 to 208,200	370,722 to 458,040	376,339 to 464,980
Dry cargo	157,650 to 184,650	346,830 to 406,230	352,085 to 412,385

Figures in table 3.2 show that the amount of maintenance cost does not change significantly in average and old aged ships, but the yearly cost of maintenance in the new ships (under 5 years old) is much lower.

According to the table 3.2, one approach to evaluate level of maintenance in ship categories is use of the estimated maintenance costs from Drewry's database. In this approach based on given estimated data for maintenance-cost, two categories of Good and Poor maintenance defined for ship categories. It can be defined that if the annual expenditure of company for any the ship is less than minimum amount of estimated maintenance-cost in the corresponding ship type, maintenance is considered as Poor and otherwise maintenance is assumed to be Good.

There is obvious relation between the need of maintenance and the time under operation in ship's machinery. A good measure for evaluation of operating time of vessel is the revenue of the owner company per year. The more accurate measure to evaluate level of maintenance can be measuring ratio of the yearly maintenance expenditure over the yearly revenue from the specific ship type (which represents how long ship has been under operation/chartered) as an alternative approach to the formerly suggested criteria. The proportion of maintenance cost per year over the annual income of the ship can be used as an indicator of maintenance level in the ship. The below fraction presents the method of quantification of suggested indicator:

$$\text{Maintenance Indicator} = \frac{\text{Annual expenditure on maintenance for the ship}}{\text{Annual income of company from the ship}}$$

Another measure to evaluate maintenance can be the fraction of total time that staff spend on maintenance in a year over the total time that they are at work. This fraction may be calculated according to the following: (Assuming staff work 8 hours per day)

$$\text{Maintenance Indicator} = \frac{\sum_{\mathrm{j}=1}^{365} \sum_{\mathrm{i}=1}^{\mathrm{N}} \mathrm{X}_{\mathrm{ij}}}{\mathrm{N} \times 8 \times 365}$$

Where:

$\boldsymbol{N}: Number\ of\ staff\ onboard$

$\boldsymbol{i}: Indicates\ the\ person\ (i)$

$\boldsymbol{j}: Days\ of\ year$

$\boldsymbol{X_{ij}}: the\ amount\ of\ time\ (hour) that\ person\ (i)\ spends\ on\ maintenance\ job\ in\ day(\ j)$

Upon the literature survey, no reliable data found regarding the yearly revenue of shipping companies or any solid record of the amount of time that staff spend on maintenance in the ships.

Maintenance in ships is schedule based. The makers of machinery recommends maintenance routine and time schedule for maintenance in all equipment. This schedule is according to the running hour in many machinery. Thus, following maintenance routine directly influences the condition of machinery and safety of ships consequently. In the study of influencing variables in ship collision probability using BBN (Hänninen and Kujala 2012), maintenance introduced as one of the risk influencing factors in BBN model. The status of maintenance quantified by measuring to what extent maintenance routines are followed. Safety culture introduced as a parent node for maintenance and state of maintenance node in the model presented by two terms of maintenance routines Followed or Not-followed, representing Good and Poor maintenance respectively. Probability of having Good or Poor maintenance depending on the state of safety culture (Parent node) quantified in the model. The report of Formal Safety Assessment published by (DNV 2006) and (DNV 2003) plus the weights by expert judgment used to quantify the maintenance factor in the BBN model. Conditional probability table of Maintenance depending the status of Safety Culture comes in the table 3.3 (Hänninen and Kujala 2012):

Table 3.3: Probability table for maintenance routines given the state of safety culture (Hänninen and Kujala 2012)

Safety Culture	**Excellent**	**Standard**	**Poor**
Followed(Good)	0.95	0.8	0.6
Not-Followed(Poor)	0.05	0.2	0.4

In another study probability of having poor maintenance defined by (Wang, et al. 2015) as a risk influencing factor within the category of human and organizational factors involved in modeling of offshore fire/explosion by use of BBN. In this article probability of deficient maintenance presented to be 8% (Wang, et al. 2015). Source of data for quantification presented to be World-Wide Offshore Accident Database and reports by HSE (HSE 2005).

3.2.2: Deficient training (2):

Training has a great influence on risk level of any operation. Poor training standard introduced as a parent node for company standards, which presented as an organizational barrier in risk analysis of human factors in offshore blowout. Probability of having poor training standards calculated based on statistical data and found to be 0.45% in offshore platform. (Baoping , et al. 2013)

In analysis of human and organizational factors associated with offshore fire and explosion by (Wang, et al. 2015) probability of deficient training calculated to be 5% in the suggested BBN model. Source of quantification of the factor presented to be World-Wide Offshore Accident Database, and data reports by HSE (HSE 2005).

3.2.3: Ship class registry (3)

Ship class registry is the authority that certifies and issues the certificates of ship and establishes and maintains the required level of standard for ships in different aspects such as technical or operational. International Associations of Classification Societies (IACSs) is an organization headquartered in London and twelve marine classification societies are members of this organization. In this regard, in most of articles, the ship class registry is categorizes in either IACS member or on-IACS member.

According to a comprehensive survey by (Li, Yin and Bang, et al. 2014) based on accident database of 120,000 vessels accounting more than 90% of commercial tonnage in worldwide scale. Three main source of aforementioned research was World Shipping Encyclopedia (WSE) (Lloyd’s Fairplay 2008), World Casualty Statistics by Lloyd’s Register (Lloyd’s Fairplay 1979-2008) and the International Maritime Organization (IMO). In total 10849 accident records collected from the three sources. The third database comprising 370,000 inspection cases in 59 countries, which were member state of three main Memoranda of Understanding (MoU) on Port State Control (PSC) under coordination of IMO. The databases analyzed in order to determine the relation between class registry and the frequency of accidents in ship. The result of study showed that probability of total loss in the ship influenced by the class registry of the ship. In the analysis of accident using

BBN, probability of total loss decreased by 10.09% when the ships were registered within IACS members and increases by 17.09 if the ships were registered in Non-IACS members (Li, Yin and Bang, et al. 2014). Conditional probability table for being registered in AICS according to statistical data on 90% of world fleet presented in table 3.4 for different types of ship.

Table 3.4: Conditional probability table for Class registry, of ship given the ship type (Li, Yin and Bang, et al. 2014)

Factors in model	**State of factor**	**Dry cargo**	**Bulk**	**Container**	**Tanker**	**Passenger**
Class registry	Non-IACS	81.89	47.80	25.68	53.53	82.27
	IACS	18.11	52.20	74.32	46.47	17.73

According to the above-mentioned database - in the study of Ship's Safety Index - analysis of accident reports showed that compared with Non-IACS members, vessels classified by IACS members are safer (Figure 3.1). This is due to the stricter regulations, which enforced by IACS members, which improves the security level of the vessels registered with them (Li, Yin and Fan 2014) .

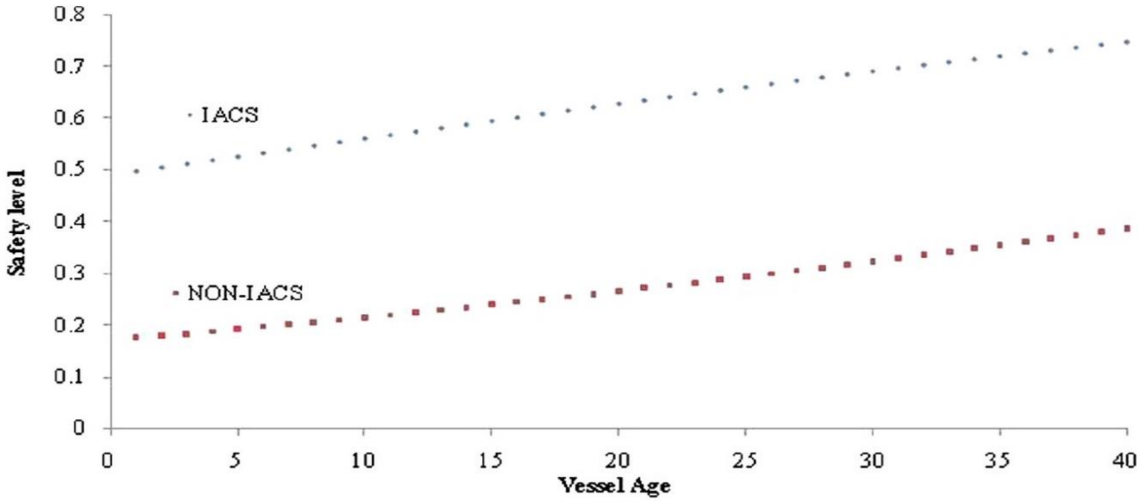


Figure 3.1: Effect of class registry (IACS/Non-IACS) on safety level of vessels (Li, Yin and Fan 2014)

3.2.4: Insufficient emergency plan and not comply with instruction (4 and 8)

According to SOLAS, all vessels must prepare muster list including name, duty and instruction for all crewmembers in case of contingency. The muster list is available in the public areas of accommodation as well as in the muster station. This regulation applies in both marine and offshore industry. Referring to Offshore Reliability Data Handbook (DNV 2009) and Worldwide Offshore Accident Database and the reported data by (HSE 2005), probabilities of having deficient emergency plan and not complying with the instruction in case of contingency presented to be 0.05 and 0.2 respectively. This result used in the quantitative risk analysis of human and organizational factors in offshore fire and explosion (Wang, et al. 2015).

3.2.5: Ship comply with the new regulation (5)

Over the time, regulation regarding safety of vessels in case of fire have been revised. New measures to decrease probability or consequences of fir have been introduced by International Maritime Organization (IMO) safety committee. New regulation regarding the use of fixed fire extinguishing system and water sprinkler system (Hyper Mist) amended in SOLAS chapter II-2 and enforced by IMO. The new regulation applies to all the ships built on or after 1.July.2002. Ships constructed before that date should comply with the chapter enforced prior the aforementioned time. Based on this criterion, ships with less than 14 years of age are expected to comply with the new regulation and ships with more than 14 years of age do not comply with the latest fire safety regulation enforced by IMO in SOLAS chapter II-2 (IMO 2016).

3.2.6: Ships flag (6)

Flag state is one of the authorities that has great influence on the level of standards that company and consequently the ship follows. The flags states categorized to three categories of White, Gray and Black according to Paris MoU’s performance list for flag states. White has the lower risk of deficiencies and Gray and Black have the medium and high level of risk of deficiencies respectively.

Modeling of port state control inspections finding and accident involvement by use of BBN was an article that used data form Finish port state control data (from 2009-2011), Baltic sea accident statistics (2004-2010) and Finland Vessel Traffic Service (2004-2008). This article used BBN to investigate the dependencies of Port State Control inspection findings and ship involvement in the accidents from the inspection, accident and incident data. In this study, flag state of ships classified in White, Gray and Black according to the accident data. (Hänninen and Kujala 2014).

Another categorization of ship's flag registry is the concept of Flag Of Convenience (FOC). Ships are registered under the flags of convenience to reduce operating costs or avoid the regulations of owner's country and are called to be open-registered. Based on this categorization ships are divided into two group of Open-Registry (under FOC) and Close-Registry (National flag). Those ships that are not close-registered are classified as open registered. In the study of safety and quality of open registered ships by (K. X. Li, The safety and quality of open registers and a new approach for classifying risky ships 1999) list of 18 countries in FOC that was covered by United Nations Conference on Trade and Development (UNCTAD) and presented by International Transport Workers' Federation (ITF). The most known countries for open registration (FOC) listed as: Antigua and Barbuda, Bahamas, Barbados, Belize, Bermuda, Cyprus, Gibraltar (UK), Honduras, Lebanon, Liberia, Malta, Marshall Islands, Mauritius, Panama, Saint Vincent, Sri Lanka, Tuvalu and Vanuatu. Regarding the safety, the average total loss of most of the open-registry fleets are higher than the world average (K. X. Li, The safety and quality of open registers and a new approach for classifying risky ships 1999). The list of FOC countries are not fixed and the above-mentioned countries are among the most known ones. Recently 34 countries declared as FOC by ITF's Fair Practices Committee. The aforementioned countries are among the declared countries (ITF 2016). The study of 20-years record on total loss accidents in different flags by (Li and Wonham 2010) shows that total loss rate in result of the accidents observed in ships with open registry countries. This study used Lloyd's Registry of Shipping Database. Database included Statistical Table (Annually 1970-1991), World Fleet Statistics (Annually 1992-1996),Casualty Return (Annually 1977-1993), and World Casualty Statistics (Annually 1994-1996) all published by Lloyd's Registry of Shipping.

Study of 130,000 ship accident from 1993 to 2008 reported in Ship safety Index by (Li, Yin and Fan 2014) . Analysis of data in this study showed that vessels registered in open registry countries have lower safety level. Because the authorities are considered to have no intention or resources in order to excise effective control over the vessels registered under their flag. According to the 90% of world's fleet data and depending on the type of ship, probability of being close registered or under flag of convenience presented in table 3.5.

Table 3.5: Conditional probability table for Flag of ship given the ship type (Li, Yin and Bang, et al. 2014)

Factors in model	**Status of factor**	**Dry cargo**	**Bulk**	**Container**	**Tanker**	**Passenger**
Flag registry	Close registered	64.13	34.87	39.52	54.95	80.63
	Open registered	35.87	65.13	60.48	45.05	19.37

Influence of flag registry on ship safety index given the age of ship presented in Figure 3.2.

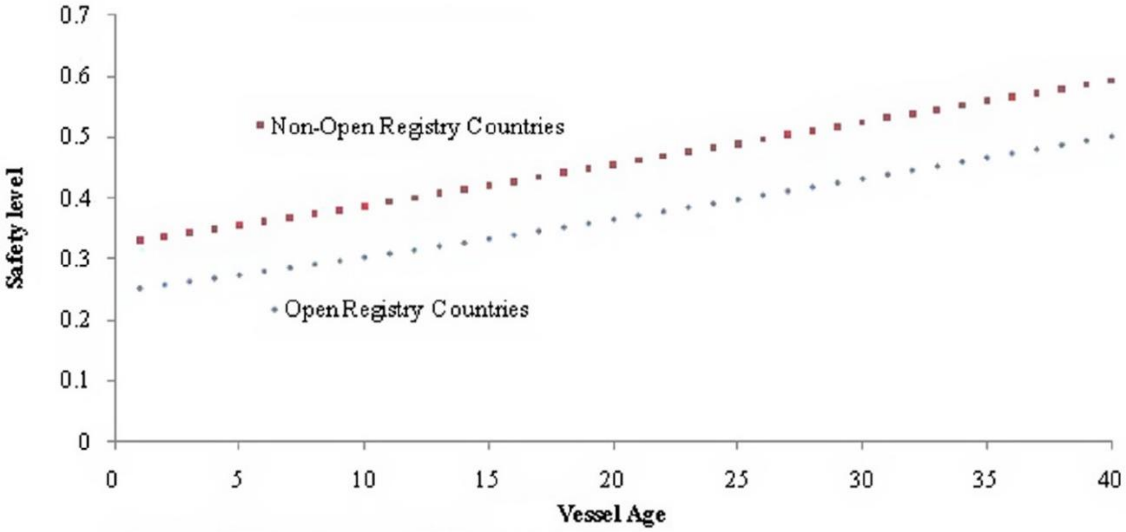


Figure 3.2: Effect of vessel age and open registry on the safety level (Li, Yin and Fan 2014)

3.2.7: Action on time and manual suppression of fire (7 and 10)

Proper action on time is one of the factors that can have significant influence on controlling the fire in marine or offshore industry. Analysis of human and organizational factors in quantitative risk analysis of offshore fire/explosion carried out by (Wang, et al. 2015). This article suggested a quantitative risk analysis framework for fire in offshore platform by use of BBN. Probability of proper action on time is one of the factors that presented in the model within the category of human and organizational factors. In this model, the terminology of "insufficient timely control" used to introduce proper action on time, which has three parent nodes. "Deficient training", "insufficient emergency plan" and "not comply with instruction" introduced as parents nodes for insufficient timely control. For quantification of the aforementioned factors, data collected from Offshore Reliability Data Handbook (DNV 2009), World-Wide Offshore Accident Database, and data reports by HSE (HSE 2005). Figure 3.3 shows the calculated probability of not having action on time in case of fire in an offshore platform (Wang, et al. 2015).

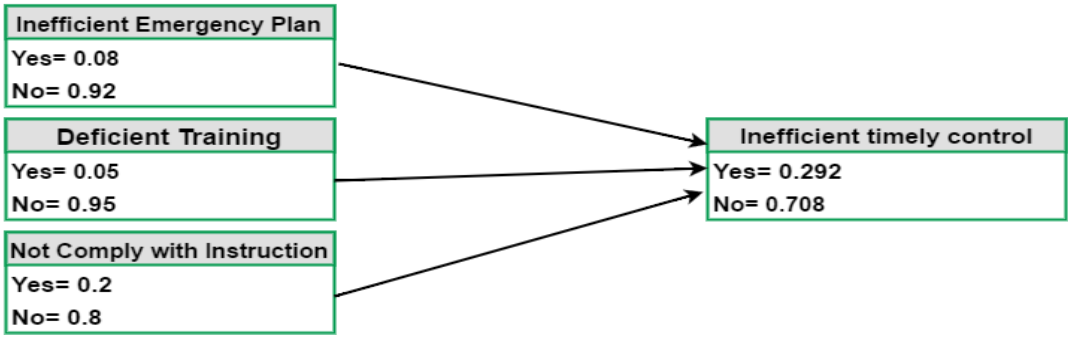


Figure 3.3: Interrelation between on-time action and organizational factors in BBN (Wang, et al. 2015)

In addition to on-time action, probability of successful firefighting by fire staff is one of the factors that influences frequency of uncontrolled fire (Table 3.6). Probability of failure of fire fighters on board depends on the scale of fire. Failure probability of fire fighters in suppressing the fire analyzed and presented in the National Fire Protection Association (NFPA) Handbook (Bush and McDaniel 1997). The result used in quantification of failure probability of manual suppression by (Hakkarainen, et al. 2009). In this study fire team classified as average trained fire department and strong fire department. For the average area of $37.16\ m^2$ of fire probability of failure calculated to be 2.995% and 0.36% respectively.

In the merchant ships there is no a professional fire fighter and the staff of ships are trained for being able fight the fire in case of contingency .All the seafarers attend the firefighting intense courses in compliance with Standard Training of Certification and Watch keeping (STCW) approved by IMO. Therefore seafarers can be considered as average trained firefighting staff with the failure probability of 2.995% in suppressing the fire in the average area of $37.16\ m^2$.

Table 3.6: Probability of fail in suppression of fire by firefighters according to scale of fire (Hakkarainen, et al. 2009)

Area of fire in ship (m^2)	Probability of failure of firefighting department	
	Average Trained	Strong fire Department
139.34	99.043%	14.6%
92.89	71.679%	4%
37.16	**2.995%**	**0.36%**
18.58	0.292%	0.1%
9.29	0.13%	0.07%
5.57	0.1%	0.059%

3.2.8: Safety culture (9)

The term of safety culture first appeared after the Chernobyl accident in 1986 (Oltedal and Wadsworth 2010). International Atomic Energy Agency (IAEA) developed the concept of safety culture and defined it as “assembly of characteristics and attitudes in organizations and individuals which establishes that, as an overriding priority, nuclear plant safety issues received the attention warranted by their significance”. In the recent years, there has been considerable interest in the safety culture especially after that IMO stated “safer shipping requires safety culture” the concept of safety culture in maritime industry gained increasing importance (Hetherington, Flin and Mearns 2006).

Safety culture presented with different definitions in the literature. For instance, Safety culture defined as: "Safety culture is a series of beliefs, norms, attitudes, roles and social and technical practices which are established to minimize the exposure of employees, managers, customers and third parties to hazard" (Dyrhaug and Holden 1996).

In another definition safety culture defined as " The safety culture of an organization is the product of individual and group values, attitudes, perceptions, competencies, and pattern of behavior that determine the commitment, the style, proficiency and organizations health and safety management" (Lee 1996).

In literatures different factors considered in order to analyze the safety culture. In the study of managing the risk of organizational accident, the tree Cs, Commitment, Competence and Cognizance referred as corner stones of safety culture (Reason 2001)

Safety culture is one of the influencing factor in the category of Human and Organizational Factors (HOFs) in risk analysis. Human and organizational factors were focus of an article that used a methodology to model causal relationships of influencing factors in offshore safety assessment. This article modeled collision risk of Floating, Production, Storage and Offloading (FPSO) vessels with the use of BBN. In the BBN model, safety culture presented as one of the basic events. The safety culture in this report quantified based on estimation by expert judgment and presented in form of fuzzy probabilities. Two possible mean value for error due to safety culture presented. The probability of error claimed to be 0.1 with the distribution of (0.09, 0.1, 0.11) which represent (Lower least likely value, the most likely value, upper least likely value). Probability of not making error due to safety culture presented to be 0.9 with the fuzzy distribution of (0.89, 0.9, 0.91). (Ren, et al. 2008)

Quantitative risk assessment of human factors on offshore blowout was subject of another article that used dynamic BBN to analyze the model. In this article, poor safety culture presented as a patent node for failure of company policy. Method of quantification of having poor safety culture was based on statistical results, which showed that probability of not having poor safety culture is 99.92%. (Baoping , et al. 2013)

In the study of effect of human fatigue on risk of maritime grounding with the use of BBN, in the subcategory of organizational influencing factors, safety culture presented as one on the root nodes in the model. Probability of having adequate safety culture presented to be 45%. This article discussed that if three influencing factors of “vessel certifications”, “manning resources” and “quality control” reach to an adequate level, the probability of having good safety culture can increase up to 60% (Akhtar and Utne 2014).

In another study, safety culture measured by handing out set of questionnaire in a randomly selected 150 vessels from the 953 vessels in the list of members of Norwegian Ship-owners’ Association’s (NSA) in 2005. Liquid tankers, general cargo and bulk carriers were in the target group of observation. The level of risk perception in each question measured on a scale ranging from one to ten. One indicating very bad and 10 indicating very good. The overall safety score in the result of study perceived as relatively good with a mean value 8 out of ten (Mean= 8 , Standard Deviation-SD =2) (Oltedal and Wadsworth 2010).

Safety Culture introduced as a variable influencing the risk of ship collision in Gulf of Finland (Hänninen and Kujala 2012). Safety culture quantified and used in the BBN for estimation of probability of ship collision. This study used the result of formal safety assessment published by (DNV 2006) and (DNV 2003) plus expert judgment to quantify the safety culture. Type of ship introduced as a parent node for safety culture in the BBN model. Safety Culture classified to tree levels of Excellent, Standard and Poor for each type of vessel. Table 3.7 presents the value of safety culture in the study of influence of variables on ship collision probability in Gulf of Finland using BBN analysis (Hänninen and Kujala 2012).

Table 3.7: Probability of safety culture in different ship types (Hänninen and Kujala 2012)

Ship Type ⇒ **Safety Culture ⇓**	**Passenger vessel**	**High speed Craft**	**Cargo ships**	**Tankers**	**Bulk**	**Container**	**Other ships**
Excellent	0.3	0.3	0.1	0.25	0.1	0.1	0.1
Standard	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Poor	0.2	0.2	0.4	0.25	0.4	0.4	0.4

According to the presented literature survey, safety culture is a dummy variable that may get different values based on the criteria that defines safety culture. It is not always possible to get a unique value for safety culture. Depending on the method of evaluating safety culture, the result may vary. Figures in the table 3.7 are the most suitable values for safety culture in analysis of uncontrolled fire in engine room within Norwegian waters. First because the values are according to type of ships which is one of the parent nodes for safety culture in suggested BBN model in this report. Second reason is that the values in table 3.7 are used to evaluate safety culture in Gulf of Finland, which is similar to Norwegian waters in terms of strictness of regulations and geographical region of the world.

3.2.9: Age of ship (11)

The older the ship gets the higher lever of degradation is observed in the machinery. Thus, age of ship and machinery influences the risk of failure in equipment. In different databases, frequency of fire according to the ship age may vary. Typically, -in analysis of accident reports - the ships age is classified in five main categories. These categories are, 0-5 years, 6-10 years, 11-15 years, 16-20 years and more than 20 years.

A comprehensive analysis of impact of ship age on accident for tankers with the Dead Weight Tonnage (DWT) greater than 60,000 carried out by (Papanikolaou and Eliopoulou 2008). In this study accident records from Lloyd’s Registry Fairplay (LRFP) and Lloyd’s Maritime Intelligent Unit (LMIU) from 1990 to 2007 taken into analysis. In addition to the type and tonnage (above 60,000) construction of ships also took into consideration in data analysis. Regarding the construction of tankers, in a separate analysis Double Hull (DH) tankers analyzed separately in addition to all tapes of construction. The result of analysis presented based on the frequency of fire per ship year (s-y) according to the ship age groups. Analysis of fire accident in tankers showed that 89% of the recorded fires in the database occurred in the aft area of the ship (Accommodation, Engine Room and Pump Room). Concerning the degree of severity, 31% of recorded fires in database (LRFP/LMIU-1990-2007) characterized by serious degree of severity and 27% resulted to total ship loss (Papanikolaou and Eliopoulou 2008). Result shows a significant increase in the fire accident frequency (s-y) when the age of ships is more than 15 years. Frequency of fire per ship year for Double Hall (DH) ships decreases to almost zero for age groups of above 15 years. This is probably because DH-tankers introduced to the market in the last 20 years and there is not that many of old DH-tankers in the world fleet that are registered by LRFP/LMIU. Figure 3.4 shows the frequency of fire accident in ship year depending on the age of the tankers.

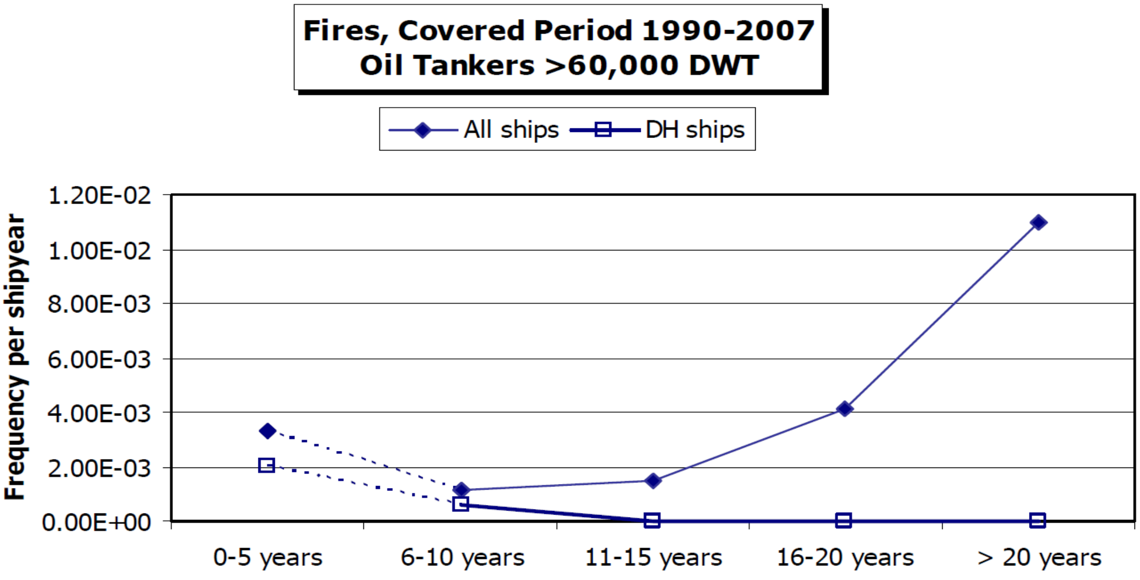


Figure 3.4: Frequency of fire event by group age (Papanikolaou and Eliopoulou 2008)

The result in figure 3.4 supports the general expectation that aging has negative influences on the safety level of ships. Analysis of 4080 observations in port state control (PSC) inspections by Swedish Maritime Administration (1996-2001) showed that vessel aging has negative impact on safety level of vessels (Cariou, Mejia Jr. and Wolff 2008). In contrary, based of study of database of about 120,000 vessels which covers more than 90% of world’s commercial fleet, (in the study of Ship safety Index) increase in the vessel age is linked with the increase in vessels safety level (Li, Yin and Fan 2014). An increase by one year in the vessel age leads to an increase by 0.001 in the safety level of corresponding ship type. This might be the reflection of the fact that survival vessels are proved to be quality or well-maintained ones (Cariou, Mejia Jr. and Wolff 2008). Vessel owners also pay more attention to and put more effort on improving the safety of older vessels than younger ones (Li, Yin and Bang, et al. 2014). The staff that are working on old vessels may so be more cautious about safety issues. Using the same database in for quantification of BBN in maritime risk analysis confirmed that increase in vessel age contributes to the decrease in the probability of occurrence of total loss in accidents (Li, Yin and Bang, et al. 2014). Figure 3.5 shows the changes in safety level of ships according to the age factor.

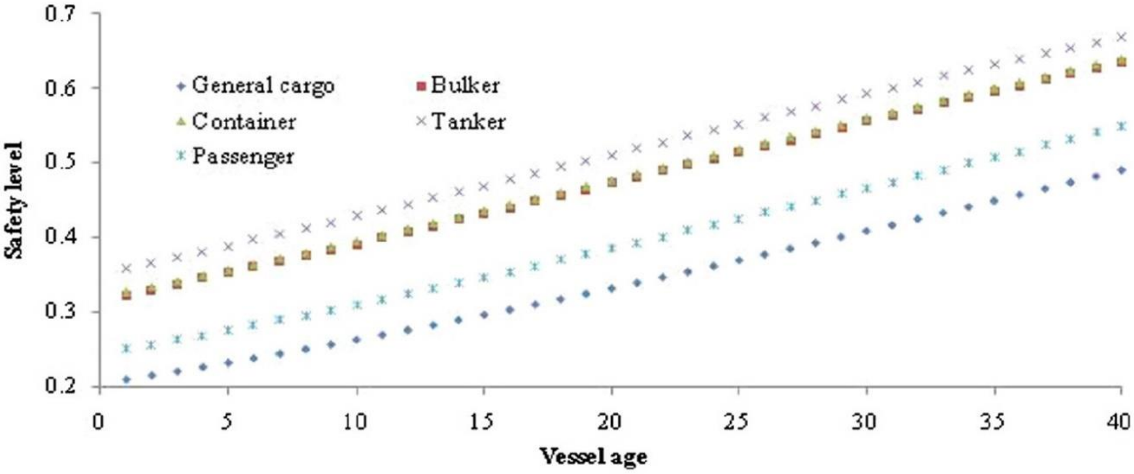


Figure 3.5: Effect of vessel age and vessel type on the safety level (Li, Yin and Fan 2014)

Study of world merchant fleet carried out by US Coast Guard (USCG) using the accident data from Lloyd’s casualty data base for tankers in the period of 1978 to 1992. Totally 763 fire reported during the 14 years period. Fire accidents analyzed in order to find any obvious relation between the age of vessels and the fire accidents. Figure 3.6 shows distribution of fire accidents according to the age of tankers.

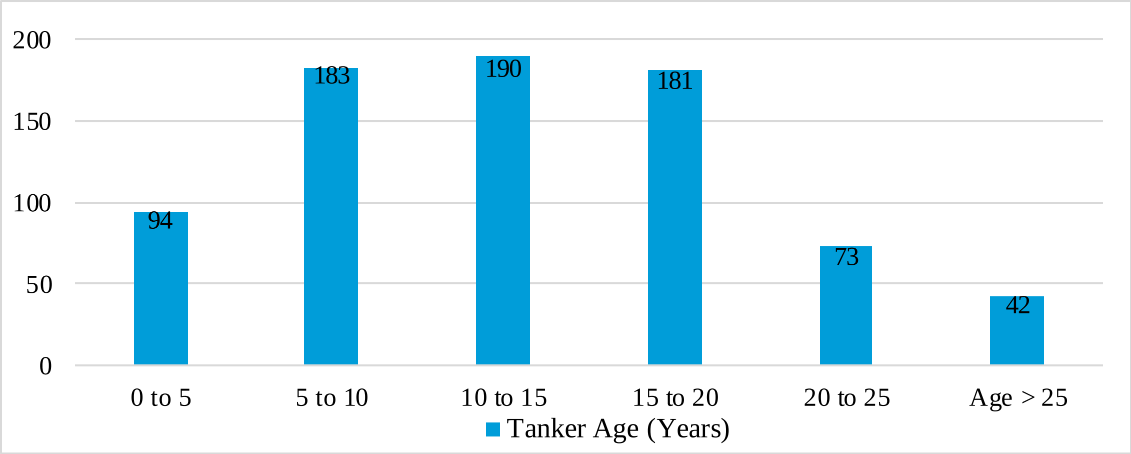


Figure 3.6: Distribution of fire in tankers based on Lloyd's Data base from (1978 to 1992) (Gentile and Dickenson 1995)

According to the figure above, distribution of fire/explosion according to the age of tankers shows that for 85% of accidents, the tanker was less than 20 years old and no linear relations observed between aging of vessels and number of reported accidents (Gentile and Dickenson 1995). (Note: The data in the figure is not normalized with respect to age group of fleet of tankers under observation)

Analysis of fire/explosion in vessels using Norwegian Maritime Authority's (NMA) database (1981-2014) presents rather different distribution of fire/explosion in respect with the vessel age. Analysis of accident database by (Stornes 2015) shows that majority of fire/explosion accident reported from the vessels with more than 25 years of age in the figure 3.7 (Note: The data in the figure is not normalized with respect to total number of ships under observation in the age groups).

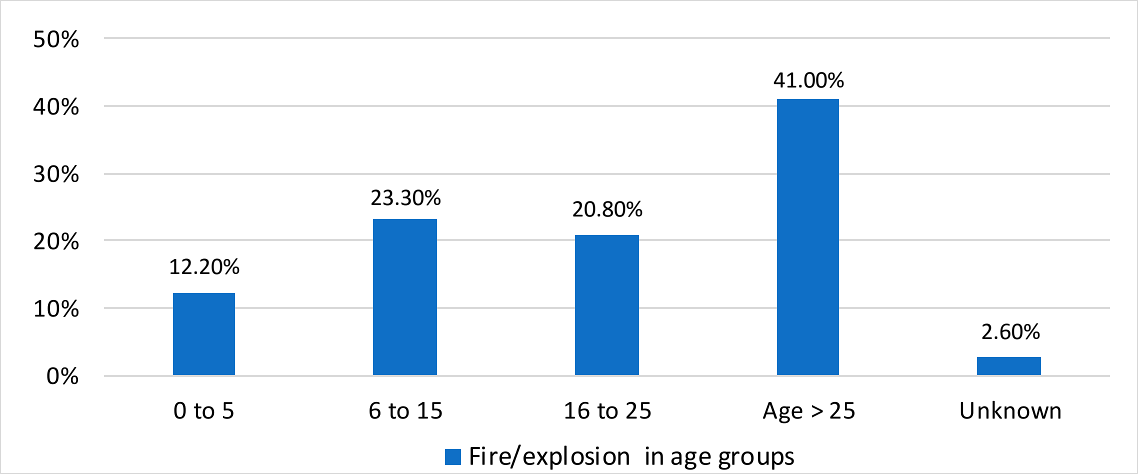


Figure 3.7: Distribution of vessels age within Fire/Explosion accidents based on NMA database 1981-2014 (Stornes 2015)

Analysis of world's fleet data showed that about more than 40% of Container ships, Bulk carriers and tankers in the world are below 5 years old. This analyze which covered about 90% of the world's fleet can be used for estimation of distribution of age in the main categories of ship type. Table 3.8 presents the world's fleet data about age of ships.

Table 3.8: Conditional probability table for Age of ship given the ship type (Li, Yin and Bang, et al. 2014)

Factors in model	Status of factor	Dry cargo	Bulk	Container	Tanker	Passenger
Age of ship	New (0-5)	18.76	41.78	43.53	42.10	20.80
	Medium (6-10)	21.13	24.10	16.53	21.56	24.45
	Old (More than 10)	60.11	34.13	39.94	36.35	54.75

3.2.10: Probability of failure of water mist sprinkler (Hyper mist system) (12)

Hyper mist water sprinkler system is one of the safety barriers in engine room that is installed to smother/cool down the fire. This system is generally used in diesel generator areas, main engine area, boiler side and incinerator side. The system activates automatically/manually when fire alarm goes off in a real demand. The water sprinkler system is used not only in ships but also on offshore platform and process industries. Probability of Failure in Demand (PFD) of water sprinkler system presented to be (PFD= 0.04) in process industry by use of OREDA database (Khakzad, Khan and Amyotte 2013).

Technically water mist sprinkler system is classified into two types, which are called Hyper Mist (Water Mist) and Hi-Fog system. In fact, Hi-Fog system is similar to Hyper Mist system but more reliable due to the Nitrogen backup containers, which are installed to pressurize supplied water in case of emergency electrical supply failure. Due to complexity of system failure rate of whole system is not specified in the reliability handbook databases. Failure rate of whole system calculated applying FTA and use of data from OREDA and Reliability Information Analysis Center (RIAC) handbook for subsystem components. Result of FTA showed the following failure rate for Water mist and Hi-Fog system (Lohrmann , Kar and Breuillard 2011).

$$\lambda_{water\,mist} = 0.0024\,\frac{1}{days} \quad and \quad \lambda_{Hi-Fog} = 0.00094\,\frac{1}{days}$$

Probability of Failure in Demand for the whole system calculated based on simplified formula as following (Rausand 2014):

$$\mathrm{PFD} = \frac{\lambda\tau}{2}$$

Where, (τ) represents the time interval between periodical (tests in hours).

Using simplified formula (Rausand 2014), Probability of Failure in Demand can be calculated for water mist/Hi-Fog system. Periodical test of water mist/Hi-fog system is carried out once a month based on SOLAS recommendation, thus $\tau = 30\ days$ ($\tau = 720\ hours$) in the calculating of PFD and using the above mentioned failure rate we get:

$$PFD_{water\,mist} = 0.036 \quad and \quad PFD_{Hi-Fog} = 0.0141$$

In analysis of failure probability of safety barrier systems, due to variety of designs and use of different level of redundancies in some designs, there is not a unique value for the result of calculation. Fault Tree Analysis (FTA) is a common measure to model the reliability in order to determine probability of Failure in Demand (PFD) of complete system. Probability of Failure in

Demand (PFD) in Water Deluge System in Liquid Petroleum Gasses LPG) vessels through Fault Tree Analysis (FTA) calculated to be $0.0189 \leq PFD \leq 0.0433$ depending in the type of actuation, pneumatic or electric, respectively (Landucci, et al. 2015). This probability used in quantitative analysis of safety barrier performance in the prevention of domino scenarios triggered by fire in marine industry (Landucci, et al. 2015).

In the calculation of fire suppression probability it is important to consider the capacity of fire fighting system and scale of fire. This means that if fire fighting system does not fail on demand, still there is a probability that fire-fighting process fails to suppress the fire due to the large scale of fire. In the study of fire in ships engine room, probability of fail to suppress in intensive extinction of fire by fixed fire extinguishing system given success in shutdown of oil supply line calculate to be 0.01 on average. In the same way probability of fail to suppress the fire with fixed fire extinguishing system given failure in shutdown of oil supply line calculated to be 0.1 (Emi, et al. 1997).

In another study, the probability that sprinkler system fail to activate upon demand in the offshore drilling rig calculated to be PFD= 0.045 with the use of failure rate data in (OREDA 2002) with using in Fault Tree Analysis (FTA) (Rathnayaka, Khan and Amayotte 2013).

3.2.11: Probability of Failure of High Expansion Foam system (13)

High expansion foam system is a fixed installation to extinguish fire in closed areas. It is mostly used in closed areas that the probability of fire in case of major leakage is high such as Purifier Room or Pump Room. The system consist of piping, nozzles, solenoid valves, pump, foam tank, etc. All of the subsystems have their generic probability of failure. Failure rate (λ) of the whole system calculated using FTA and presented to be ($\lambda = 0.0072 \frac{1}{days}$), (Lohrmann , Kar and Breuillard 2011).

According to the abovementioned failure rate, and considering 7 days periodical inspection routine $(\tau = 7)$, with the use of simplified formula (Rausand 2014) PFD of high expansion foam system can be calculated as $(PFD_{Foam\ system} = 0.0252)$

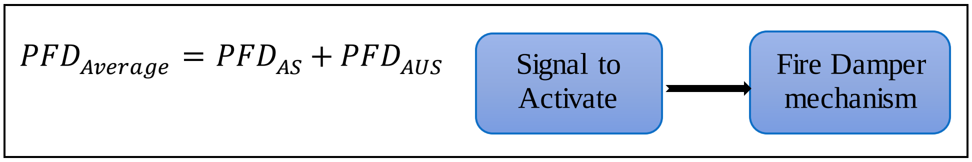
3.2.12: Failure of fire dampers (14)

Fire dampers are set of flaps that are installed inside the supply air ducts of engine room. Upon the detection of fire dampers block the air supply to engine room to eliminate escalation of fire. The type, application and design of fire dampers are similar in offshore, marine, nuclear and most of heavy industries. A comprehensive study of fire damper closure using risk analysis in evaluation of different design alternatives and various sizes for application in chemical process or nuclear facilities carried out by (Chang, Hunt and Jahn 1994). Later result of the study used by (Rathnayaka, Khan and Amayotte 2013) to quantify the probability of failure in demand for fire/smoke dampers in analysis of fire suppression in a drilling rig. The probability of failure in fire damper system (PFD) split into failure of two function (Rathnayaka, Khan and Amayotte 2013):

1- No automated action (signal) to activate fire/smoke dampers:
$PFD_{Activation\ Signal\,(AS)} = 0.001$

2- Fire/smoke damper flaps fail to actuate upon receiving the activating signal:
$PFD_{Activation\ Upon\ Signal\,(AUS)} = 0.0031$

In order to calculate the total $PFD_{Average}$ for Safety Instrument Function (SIF) of fire damper system using reliability block diagram, total $PFD_{Average}$ of channel is equal to sum of PFD of the two subsystem elements in the channel (Rausand 2014).



$$PFD_{Average} = PFD_{AS} + PFD_{AUS}$$

Figure 3.8: Reliability block diagram of fire damper system

According to figure 3.8, we get $PFD_{Total} = 0.0041$ for the whole fire damper system.

3.2.13: Probability of failure of fire pump (15)

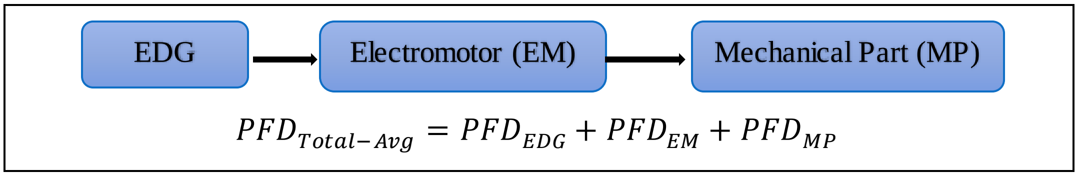
All vessels are equipped with Emergency Fire Pump, which is installed in a rather safe compartment such as Steering Room in order to supply water for firefighting in case of fire in engine room. Fire pump consist of two main elements. Electromotor and the mechanical part including shaft, casing, impeller, mechanical seal and all additional mountings. OREDA distinguishes between these two main subsystem elements in calculation of PFD.

Average PFD of electrical motor for water firefighting pump presented to be ($PFD_{Avg-Electromotor} = 8.8 \times 10^{-3}$) in (OREDA 2015).

Probability of Failure to start on Demand (PFD) of centrifugal water firefighting pump (Mechanical part) presented to be ($PFD_{Avg-Mechanical\ part} = 3.6 \times 10^{-3}$) in (OREDA 2015).

In case of fire in engine-room, emergency fire pump receives the electrical power supply from Emergency Diesel Generator (EDG), which is usually installed outside of engine room area. Failure of EDG results in failure of Emergency fire pump to start. In calculation of failure probability of firefighting pump, we need to consider the probability of failure in functioning of EDG. EDG may fail to supply power due to many failure moods like Fail to start, Fail to synchronize, Faulty output voltage, etc. The average probability of fail to supply power presented to be $PFD_{Avg-EGD} = 1.4 \times 10^{-2}$ for EDG with capacity of less than 1000 (kVA).

In order to calculate the total average probability of failure of fire pump we need to consider the PFD in tree elements of EDG, Electromotor and Mechanical element of pump. Using reliability block diagram, failure of safety instrument function calculated in the figure 3.9 (Rausand 2014):



$$PFD_{Total-Avg} = PFD_{EDG} + PFD_{EM} + PFD_{MP}$$

Figure 3.9: Reliability block diagram of fire pump

According to the figure above, the average failure probability of functioning on demand of water firefighting pump calculated to be:

$$PFD_{Total-Avg} = 2.64 \times 10^{-2} = 0.0264$$

Ship in load/ ballast condition:

No evidence found in the literature survey regarding relation of loading status of vessel and probability of initiation of fire in engine room. Being in load or ballast condition may influence the probability of failure of emergency fire pump in supplying water. This is due to change in the value of negative suction head in the pump in result of change in ship's draft. The increase in negative suction head of pump might lead to loosing vacuum and no discharge consequently when the pump starts. These failure moods are presented in (OREDA 2015) as Erratic output and Low output. In calculation of overall PFD average in mechanical part of the pump, these failure moods taken into account. Therefore, the node of ship in loaded or ballast condition taken away from the model for simplification.

3.2.14: Probability of detection of fire (16)

Most of the fire detectors in the engine room are smoke detectors. Smoke detectors are installed with a certain distance from each other depending on radius of the coverage area of smoke detectors. Number of detectors per area depends on how big the area is. Probability of detection of fire formulated in the analysis method by (Emi, et al. 1997) and later used by (Charchalis and Czyz 2011) in the analysis of fuel oil and diesel oil systems fire hazard in sea vessels engine room. Probability of fire detection calculated with the following formula (Emi, et al. 1997):

$$Pd = 1 - (1 - P_{det})^{N_d} \ , for\ N_d \geq 1$$

$$Pd = P_{det} \times 0.5 \ , for\ N_d = 0$$

Where:

$P_{det} = Coeficient\ of\ fire\ detection = 0.8$

$N_d = Number\ of\ fire\ detectors$

According to the above formula, considering at least one detector per unit of area, probability of detection based on number of installed detectors are given in table 3.9.

Table 3.9: Probability of detection of fire in area with different number of detectors

Number of detectors	1	2	3	4	5	6
Probability of detection (P_{det})	0.8	0.96	0.992	0.9984	0.99968	0.999936

The above-mentioned equation used to calculate the probability of gas detection with installed gas detectors in case of gas leakage in the offshore facility by (Paik, et al. 2011).

The detector system consists of detectors, connections, cables, logic solver, alarm and back up battery. In case of failure of any of these elements, the whole system may fail and the failure is normally regarded as Dangerous Undetected (DU) meaning that failure will not be detected until the real demand (fire) occurs or during the periodical function test. Due to this fact fire alarm system is tested every week during Saturday Routine in ships. Probability of failure of whole fire alarm system calculated using Fault Tree Analysis (FTA) by assigning reliability data to subsystem from ORERA and Reliability Information Analysis Center (RIAC) handbooks assuming that all components in subsystem follow exponential distribution in their failure rate. Failure rate for the whole Detector system (fire alarm system) calculated in fault tree by use of BlockSim software and presented to be as following (Lohrmann , Kar and Breuillard 2011):

$$\lambda_{whole\ detection\ system} = 0.0029\ \frac{1}{days}$$

By use of simplified formula (Rausand 2014) and considering 7 days of time interval ($\tau = 168\ hours$) between the tests (Saturday routine) we get:

$$PFD_{fire\ detection\ system} = 0.01015$$

In another study, probability of failure of heat/smoke detectors system in a process facility in case of fire due to release of hydrocarbons from valve, pump or separator while or after maintenance calculated. This situation is similar to engine room. The probability of failure of smoke detectors in the area presented to be 1% in analysis of risk of human error in pre and post maintenance procedures of process facilities (Noroozi, et al. 2013). The calculated probability of failure of smoke/heat detector system in report by (Noroozi, et al. 2013) confirms the calculated PFD with simplified formula.

In the study of safety of process systems, probability of failure of fire alarm in in case of fire in process industry evaluated from (OREDA 2002). In this article probability of failure in demand of fire alarm presented to be 0.0013 in process industry (Khakzad, Khan and Amyotte 2013). In this study, the presented probability is for fire alarm and not for the whole detection system.

3.2.15: Probability of failure of quick closing valves (17)

Quick closing valves are designed to cut off the fuel/ oil supply. These valves can be actuated remotely from accommodation (Foam Room). Quick closing valves are inspected monthly meaning that ($\tau = 30 \times 24 = 720\ hour$). Reliability of fail to close on demand calculated using simplification formula (Rausand, Reliability of Safety-Critical Systems 2014) and failure rate of quick closing valves calculated to be ($\lambda = 2.2062 \times 10^{-6} per\ hour$) (Anantharaman, et al. 2015). PFD of Quick Closing Valves (QCV) calculated to be ($PFD_{QCV} = 0.000794$).

3.2.16: Ship in port or not in port (sailing or stopped)-(18)

Probability of fire in engine room may vary in the port or when ship is not alongside (In sailing). This can be due to number of running machineries in engine room. For example, main engine is always stopped when the ship is alongside. Statistical data shows that probability of fire is higher when ship is in sailing. Table 3.10 shows statistical distribution of fire in ship according to location status of ship (Non-port/ port) based on analysis of different databases (Hakkarainen, et al. 2009).

Table 3.10: Location of ship when fire originated (% of all fires) (Hakkarainen, et al. 2009)

Location of the ship	Bureau Véritas (CEPN-IPSN) 1978-1988	Lloyd's (SNL) 1979-1993	Lloyd's(SRD) 1984-1993
Port Fires	43.4%	38.2%	37.6%
Non-port fire	56.6%	61.8%	62.4%

It can be seen that the statistical analysis of Norwegian Maritime Authority (NMA) database from 1981 to 2014 for fire accident reports in Norwegian waters confirms that majority of fire accidents happened when ship was not alongside. Distribution of the reported fire accidents during 1981 to 2014 by NMA according to ship movement status is shown in the table 3.11.

Regarding the severity of fire, 39.4% of fires resulted in no damage or less damage and 60.6% of fires resulted in severe damage or partial/total shipwreck (Stornes 2015).

Table 3.11: Distribution of severity within fire accidents (Stornes 2015)

Ship status	Under way	Maneuvering	Fishing	In port	Unknown
Percentage of fire accidents	35.5%	4.1%	11.6%	28.8%	20%
Total	Total Non-port fire= 51.2%			In port = 28.8%	Unknown=20%

In the risk analysis of fire in engine room in the Norwegian waters or any specific area, the accident statistical data is not that helpful since it does not represent the average distribution of state of ships (in sailing or stopped) in the region of interest. In order to determine the average percentage of being in sailing in compare with being in a stop position for analysis of fire in the region of interests, the statistical recorded data for movement of vessels in that area needs to be analyzed.

This analysis includes analyze of recorded data in Automatic Identification System (AIS) for the area of under investigation.

3.2.17: Type of ship (19):

(Tanker- Passenger- Container- offshore services etc).

In the analysis of safety of ships according to the ships type as shown in figure 3.10, size of vessel does not significantly influence the level of safety in vessels when the Gross Tonnage (GT) of ships goes more than about 30,000 tons. In contrary, type of vessels has influence on the level of safety. The analysis (Figure 3.10) shows tankers have the highest level of safety and general cargo vessels have the lowest level of safety. Container vessels and Bulk Carriers both have the second rank in the group and Passengers ships have the third rank in the total five type of vessels (Li, Yin and Fan 2014).

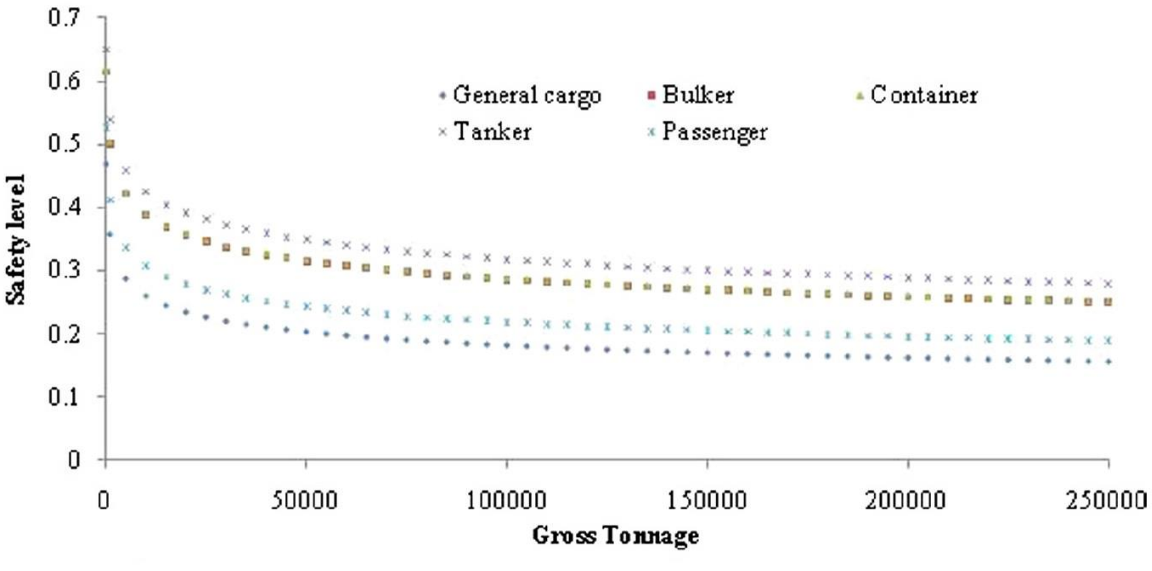


Figure 3.10: Effect of tonnage and vessel type on safety level (Li, Yin and Fan 2014)

Study of fire accident in ships according to Det Norske Veritas (DNV) database from 1992-2004 including 300 reports of fire accident for more than 25000 ship-year (s-y) showed that frequency of fire in passenger ships and tankers is more than other vessels. According to this study, 63% of all reported fires in the database, occurred in engine room. Cargo area and Accommodation had the second and third rank in reported fires with 27% and 10% respectively in the database. (Hakkarainen, et al. 2009). Figure 3.11 shows the frequency of fire per ship-year according to different type of ships using DNV (1992-2004) database.

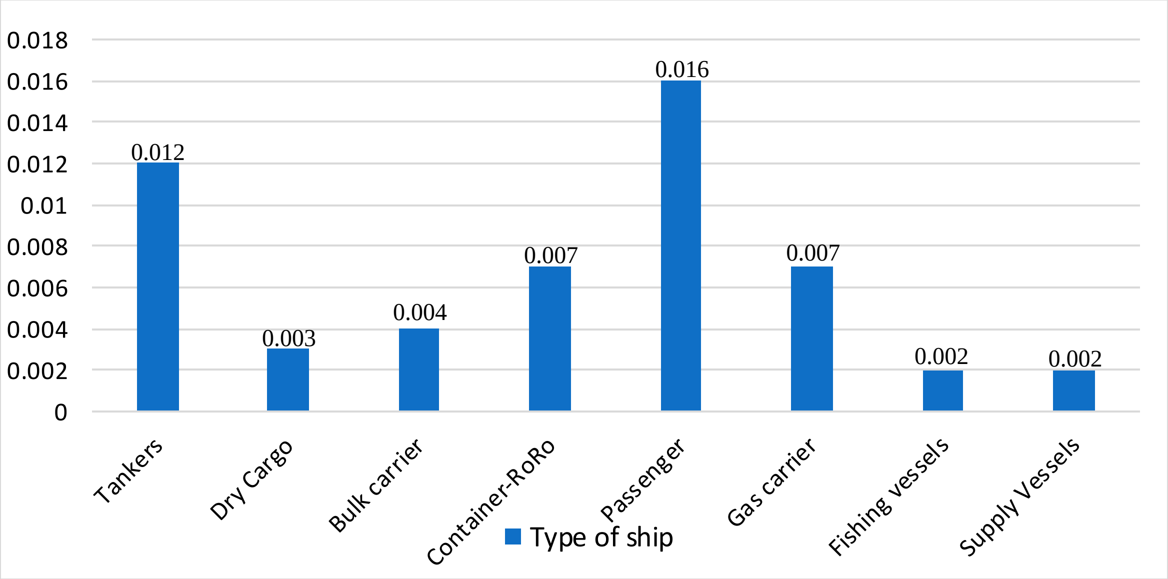


Figure 3.11: Fire frequency per ship-year according to DNV(1992-2004),(Hakkarainen, et al. 2009)

3.2.18: Leakage of hydrocarbon (20 and 21)

Initial releases rate in case of leakage or crack in the pipes depends on the pressure inside the pipe/equipment, size of the hole/crack and phase of release (viscosity of liquid). In the offshore and marine vessels hydrocarbon releases are usually gaseous, liquid or two-phase. In the grope of hydrocarbons, hydrocarbon chains in the range of C1 to C4 are normally in gas phase in atmospheric pressure and temperature. Hydrocarbons with the carbon chain range from C5 and C6 are normally in two-phases depends on the pressure and the temperature of the hydrocarbon. The third and main grope of hydrocarbons that is used as fuel in marine and offshore vessels are hydrocarbons with the chain of bigger than 6 like C7, C8 etc. which are normally in the liquid phase.

Different equipment in the engine room with their fuel/oil connections have various probabilities of starting a leakage. This is due to the different level of vibration, temperature and other specification of machinery and piping connections. Shipbuilding Research Association of Japan and Nippon Kaiji kyokai (Class NK) carried out a research with the aim of contributing to the work of IMO Fire Protection standards (FP) to amend chapter II-2 of Safety of Life at Sea (SOLAS). In the study of engine room fire by Nippon Kaiji kyokai (Class NK) probability of leakage in the engine room formulated by (Emi, et al. 1997). In order to quantify the probabilities of each event, a series of analysis including investigation nearly 800 fire hazards in duration of 13 years and geometrical analysis on oil spill and hit sources conducted. The result of study by (Emi, et al. 1997) submitted to IMO. This report introduces a technique for assessing the relative probability/frequency ratio at each probable location where fire may occur (IMO 2006). Result of this study later used by (Lindgren and Sosnowski 2009) in safety assessment of fire and explosion in machinery space for oil tankers and container vessels. The results also used by (Charchalis and Czyz 2011) in the Analysis Methods of Fire Hazard of Fuel Oil and Diesel Oil Systems in Sea Vessels Engine Room. In these articles probability of leakage of flammable liquid in contraction with the ignition sources calculated with the following formula (Emi, et al. 1997):

$$\boldsymbol{P_l} = \frac{R_{max} - \lambda}{R_{max}} \times \frac{2\emptyset + \omega}{360} \times 0.5 \times f$$

Where: R_{max}=Spray reach and calculated as:

$$R_{max} = \frac{V_l^2}{g} \times \sin(2\theta),$$

Which:

$P_l = Probability\ of\ leakage\ in\ ship\ year(s-y)$

$V_l = liquid\ leakage\ velocity,$

$\theta = Centeral\ release\ angle\ in\ horozontal\ plane\ for\ flanges\ and\ screw\ type\ joints.$

θ: $calculatedto\ be\ on\ average\ 30°.$

$g = gravitational\ acceleration.$

$\lambda = Is\ the\ reduced\ distance\ between\ the\ leakage\ point\ and\ a\ source\ of\ ignition.$

$\lambda = 1.5\ for\ the\ real\ distance\ l \leq 3m, and\ \lambda = 4.5\ for\ l > 3m.$

$\emptyset =$ *Liquid spray cone angle in horizontal plane (In degrees) which calculated to be on average:*

$\emptyset = 60\ for\ Flange\ joints, \emptyset = 10\ for\ Bolted\ joints.$

$f = Sheltering\ effect\ coeficient, 0.0625 \leq f \leq 0.125, (depend\ on\ the\ l \leq 3m\ or\ l > 3m)$

$\omega =$ *Two-dimensional Coefficient of shape (2D) of ignition source seen from release point (Table 3.12).*

Table 3.12: Quantity of ω in different locations

ω	L$\leq 3m$	L$> 3m$
Boilers/Incinerator	120	60
Main Engine	80	80
Diesel Generators	80	60
Others	60	30

In order to calculate the probability of leakage with the given formula the Liquid Leakage Velocity (V_l) needs to be quantified first. Based on Bernoulli Theorem, velocity of leakage of liquid from pipe (V_l) is independent of the crack/hole size and just depends in differential pressure of liquid inside the pipe and the outside area and also the density of liquid which is function of temperature. The velocity of liquid in leakage out of pipeline derived from the Bernoulli Thorium as following (Emi, et al. 1997):

$$V_l = C_d \sqrt{2\left[\frac{10^5(P_{in} - P_{out})}{\rho}\right]} \quad , C_d = Radiation\ coefficient(C_d = 0.6)$$

Where ρ is the density of fluid, P_{in} and P_{out} are the absolute pressure inside and outside the pipe respectively (In unit of Bar). Density of Heavy fuel oil (HFO) calculated to be 980 $\frac{Kg}{M^3}$ in the temperature of $130℃$ (Kontoulis, Kazangas and Kaiktsis 2013). The relative fuel pressure inside the pipeline that is connected to main engine is on average 8 Bar and for Generators is 7 Bar on average (IMO 2004). This pressure can vary for Boiler between 2 Bar to 12 Bar depending on the load of Boiler (In Tankers). Therefor the average value of 8 bar is considered as the average differential pressure of liquid inside the pipeline and the outside area. The outside pressure in the Engine room is Atmospheric pressure.

Considering average pressure of 8 bar in the pipeline, the velocity of leakage (V_l) calculated to be $24.24\ \frac{m}{s}$. According to the abovementioned formula and given parameters, probability of leakage calculated in table 3.13.

Table 3.13: Probability of leakage (P_l)in ship year(s-y)

Compartments	For L$\leq 3m$ from the hot spot		For L$> 3m$ from the hot spot	
	Flanged joints	Bolted joints	Flanged joints	Bolted joints
Main engine	0.0337	0.0168	0.0158	0.0079
Diesel Generators	0.0337	0.0168	0.0143	0.0063
Boiler	0.0404	0.0236	0.0143	0.0063
Incinerator	0.0404	0.0236	0.0143	0.0063
Other sources	0.0303	0.0135	0.0119	0.0039
Purifier Room	0.0303	0.0135	0.0119	0.0039

3.2.19: Probability of ignition (22):

For the initiation of fire, presence of burning material (Hydrocarbon), air (Oxygen) and source of energy (Ignition) is crucial. Air is always available in engine room. In case of release of hydrocarbon probability of ignition is one of the factors that needs to be evaluated in the model.

Assessment of risk of ignition in case of release of hydrocarbons is one of the key steps in risk analysis of fire in any machinery area in both onshore and offshore.

Study of human and organizational factors in quantitative risk analysis of offshore fire and explosion using BBN carried out by (Wang, et al. 2015). In this study, probability of basic events in the BBN collected from (DNV 2009) and (HSE 2005). Probability of ignition in case of release of hydrocarbons presented to be 30.3% due to external heat (Hot spot) and 25.8% in case of contacting with electric spark (Wang, et al. 2015).

Probability of ignition in a process facility in case of release of hydrocarbons from valve, pump or separator while or after maintenance (which is similar to engine room) calculated to be 10% in analysis of risk of human error in pre and post maintenance procedures of process facilities by (Noroozi, et al. 2013).

Among the available models for estimation of probability of ignition, a few are based on the assumption that ignition probability is solely function of release rate or size of flammable gases while the others incorporate some additional features such as location of ignition source, density, ignition potential, type of ignition sources. Development of method for determination of on-site ignition probabilities was subject of an article published by (Daycock and Rew 2004). In this article, on-site ignition probability in offshore installations formulated and developed in such a way that can be implemented in risk analysis models. Locations such as process area, storage area, accommodation block, kitchen facilities, boiler house and office considered in the model. The formulated equation for probability of ignition by (Daycock and Rew 2004), later used to estimate the ignition probability for consequence assessment of fire/explosion in offshore platform by (PULA, et al. 2006). The equations used in the model described in the following:

The probability of ignition is:

$$P(t) = 1 - Q(t)$$

In which $Q(t)$ presented as follow:

$$Q(t) = \exp(-\mu A\{1 - (1 - ap)e^{-\lambda pt}\})$$

In which **A** is the proportion of flammable cloud area containing random distribution of ignition sources over the whole area of analysis (Engine Room). $\boldsymbol{\mu}$ is average number of ignition sources, $\boldsymbol{p}$ is ignition potential of a source (0-1), $\boldsymbol{a}$ is the rate of activation of source and $\boldsymbol{\lambda}$ is proportion of time that the source is activated. The amount of aforementioned parameters calculated for different cases by (Daycock and Rew 2004) in their article.

The amount of **A** estimated about 20% for main engine, 5% for purifier room, 10% for boiler 15% for diesel generators and 5% for incinerator and the cloud area for any point of leakage (near electrical equipment) estimated to be 5% of all engine room area. Table 3.14 presents the value of aforementioned parameters.

Table 3.14: Values of parameters in ignition probability equation for different locations

Area	***Ignition source***	$\boldsymbol{p}$	$\boldsymbol{a}$	$\boldsymbol{\lambda}$	$\boldsymbol{\mu}$	**A**
Boiler	Boiler	1.00	1.00	0.002	1	10%
Incinerator area	Incinerator	1.00	1.00	0.002	1	5%
Main Engine	Heavy equipment	0.3	1.00	0.028	1	20%
Auxiliary Engines	Heavy equipment	0.3	1.00	0.028	1	15%
Purifier room	Medium equipment	0.4	1.00	0.035	12	5%
Electrical equipment	Light equipment	0.05	1.00	0.056	2	5%

Most of the given data for ignition source in (Daycock and Rew 2004) model have a great possibility to remain the same irrespective of condition such as offshore or onshore condition (PULA, et al. 2006).

Ignition takes place when leakage occurs and remains undetected. Time of detection of any leakage can vary from zero to 7 hours=420 minutes. The longest time is when ship is in Un-Manned Ship (UMS) operation during the night. In average watch keeper takes an inspection round every one hour (60 minutes) during the watch. Thus, we can assume that time of detection is a random variable which is PERT distributed with parameters (L=0, M=60, H=420). Because the detection time is random variable, in order to calculate the probabilities of ignition with the given formula, mean average detection time calculated by the use of **Mont Carlo Simulation (MCS)** for the above parameters. The result of MCS for mean detection time in 9000 simulation showed at mean value is 116.77 minutes with the standard deviation of 24.45 minutes. Figure 3.12 shows the probability density function in MCS.

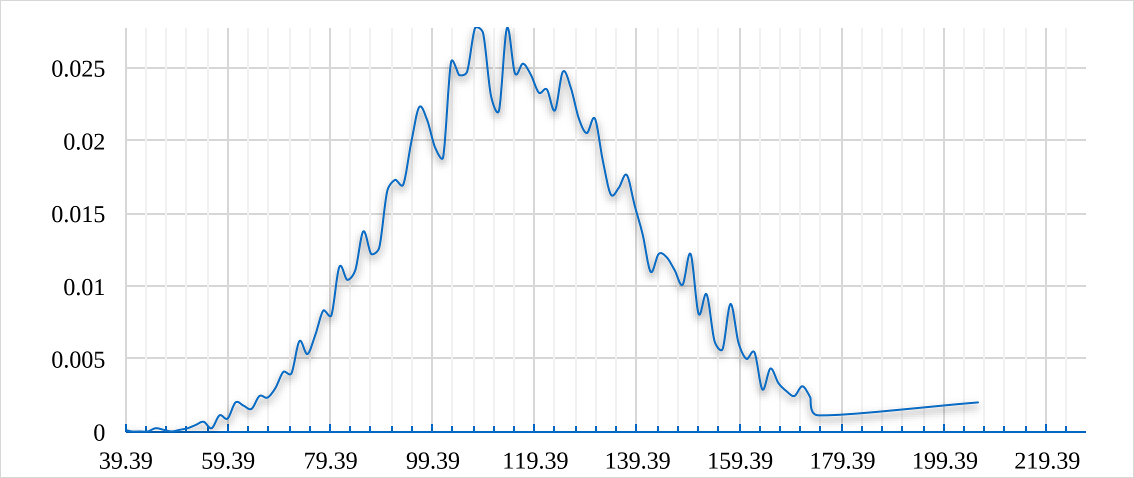


Figure 3.12:Probability density function for mean time of detection in MCS

Using the formula for calculation of the probability of ignition, we get the probabilities in table 3.15 for each location in case of leakage of hydrocarbon. Table 3.15 shows that purifier room is more prune to fire than the other compartments. Main influencing parameters in the formula are number of hot spots in the area and the ratio of the area with the nominated density of hot spots over the whole area of calculation. Therefor probability of ignition in case of leakage in the purifier room is more than boiler area and main engine area due to higher number of hot spots in that area.

Table 3.15:Probability of Ignition in different hot compartment of Engine Room

Boiler	**Incinerator**	**Main Engine**	**Auxiliary Engines**	**Purifier Room**	**Electrical Equipment**
0.095162582	0.048770575	0.176899325	0.135848837	0.447861008	0.095038297

Quantification methods for probability of ignition is not unique in the literatures. Probability of ignition during an interaction between flammable liquids release in engine room and the sources of ignition calculated with different formula in analysis of fire hazard of fuel oil and diesel oil system in sea vessels engine room by (Charchalis and Czyz 2011). In this article, probability of ignition calculated with the following formula:

$$\boldsymbol{P_i = P_{it} \times C_t}$$

Where :

$\boldsymbol{C_t}$: Coefficient taking into consideration a temperature of the liquid. For the liquid temperature of **T** the coefficient $\boldsymbol{C_t}$ is given in the table 3.16.

Table 3.16: Coefficient of C_t for different temperatures

Temperature (T)	$130° \leq T$	$100° \leq T \leq 130°$	$80° \leq T \leq 100°$	$T \leq 80°$
$\boldsymbol{C_t}$	1.0	0.8	0.6	0.4

$\boldsymbol{P_{it}}$: Coefficient taking into consideration the distance between source of leakage and source of ignition. Table 3.17 shows different values of $\boldsymbol{P_{it}}$ in different locations.

Table 3.17: Coefficient of distance (P_{it})

Value of $\boldsymbol{P_{it}}$ in different sources	L$\leq 3m$	L$> 3m$
Boiler	0.01	0.001
Incinerator	0.01	0.001
Main Engine	0.005	0.005
Diesel Generators	0.005	0.001
Purifier Room	0.001	0.0005
Others	0.001	0.0005

Considering the above-mentioned formula, we get the following probabilities of ignition.

(Usually, fuel oil is supplied to Main Engine/Generators/Boiler/Incinerator with the temperature in the range of 120°C to 135°C, therefore we consider on average $\boldsymbol{C_t} = 1.0$).

In the rest of other sources, the temperature is between 80° to 130°, therefore coefficient of $\boldsymbol{C_t}$ for other sources is between 0.4 to 1.0.

Probability of ignition in Engines and Boilers: $\boldsymbol{P_{i-min}} = 5.0 \times 10^{-3}$, $\boldsymbol{P_{i-max}} = 1.0 \times 10^{-2}$

For Other Sources of ignition we get the below table 3.18.

Table 3.18: Value of probability of ignition (P_i) in different locations

Value of P_i	**L$\leq 3m$**		**L$> 3m$**	
Boiler	0.01		0.001	
Incinerator	0.01		0.001	
Main Engine	0.005		0.005	
Diesel Generators	0.005		0.001	
Purifier Room	0.001		0.0005	
Other sources	**T= 80℃**	**T= 130℃**	**T=80℃**	**T=130℃**
	0.0004	0.001	0.0002	0.0005

As can be clearly seen the result of calculation with this formula is different with the calculated conservative probability of ignition in Boiler compartment by (Daycock and Rew 2004). This variety in the numbers is because of the time gap (about 2 hours) between initiation of leakage and occurrence of ignition. This time gap will cause mass release of hydrocarbon. When the time passes the amount of leaked liquid accumulates and probability of ignition goes higher. In the formula by (Emi, et al. 1997) the time of leakage did not considered in the evaluation.

3.2.20: Probability/Frequency of initiation of fire (23)

Fire starts, when leakage occurs and flammable liquids get contact with a source of energy (which results in ignition). In quantitative risk assessment of hydrocarbon fire/explosion in offshore installations frequency of fire calculated based on the total frequency of leaks and probability of ignition as follow (Paik, et al. 2011).

$$\boldsymbol{F}_{fire}^{\text{total}} = \boldsymbol{F}_{leak}^{\text{total}} \times \boldsymbol{P}_{ignition}^{\text{total}}$$

Where,

$\boldsymbol{F}_{fire}^{\mathrm{total}}$ =Total frequency of fire event $(year^{-1})$

$\boldsymbol{F}_{leak}^{\mathrm{total}}$ =Total frequency of leak event$(year^{-1})$

$\boldsymbol{P}_{ignition}^{\mathrm{total}}$ =Total probability of ignition

Chapter 4

BBN Method description

4.1: Introduction

Uncertainty is always an indisputable part of decision making. In analysis of any uncertain event, some events are influenced by the other events and they have impact on the uncertainty of their decedents. In addressing tasks such as diagnosis, predicting, decision making, data mining etc. there is a need for a model that can present the correlation between the factors for showing the interrelation and dependencies of different events on each other.

One of the recommended solutions for dealing with the correlation of ancestor and decedent events in analysis of uncertainty is using probabilistic network. Probabilistic networks not only have the ability of expressing causal interaction and dependencies between contributing facts, but also can be analyzed qualitatively and quantitatively. As a solution, Bayesian Network developed as an extension to predicate logic based on deterministic production rules.

Bayesian Network has been applied for many applications from past to now. One of the earliest applications of BBN was in medical diagnosis based on observation of symptoms. The dimension and complexity of the models were high such that they had over hundreds of nodes in some cases (Friis-Hansen 2000).

This chapter presents an introduction to Bayesian Belief network (BBN) as a powerful decision making tools which has a wide range of use in all realms of researches.

4.2: History of Bayes Theorem

Name of BBN comes from the name of Tomas Bayes, an English statistician, philosopher (1701-1761) who is known for formulating his specific theorem in inverse probability which later named Bayesian theorem (Wikipedia, Bayes' theorem 2016).

The idea of Tomas Bayes later developed by Pierre-Simon Laplace who introduced the modern formulation in 1812 which defined as follow:

$$\boldsymbol{P(A|B).P(B) = P\ (A,B)}$$

Where by symmetry we get:

$$\boldsymbol{P(B|A).P(A) = P\ (A,B)}$$

Combination of the two aforementioned equalities gives the Byes Formula as following:

$$\boldsymbol{P(A|B) = \frac{P(A).P(B|A)}{P(B)}}$$

Where **P(A)** and **P(B)** are probabilities of events A and B, independent of each other. $\boldsymbol{P(A|B)}$ is the conditional probability that A given B is true. Likewise, $\boldsymbol{P(B|A)}$ is the conditional probability that B given A is true.

4.3: Development of Bayesian belief Network

In the late 1980s Judea Pearl summarized the properties of Bayesian Network and established BBN (Wikipedia, Bayesian network 2016).

In simple word Bayesian Belief Network (BBN) is a graphical model that shows causal correlation between the main causes and the one or more outcomes in the model. It made up on nodes and direct arcs, which indicate the condition and influence respectively.

4.4: Objectives of using BBN in risk analysis

- Identification of all facts that can directly or indirectly have considerable influent on a hazardous event or accident.
- Clarify the correlation of influencing factors.
- Define and calculate the status, probability and frequency of each node and distribution of them if applicable.

- Analyze the model in order to ascertain the most critical contributor to the probability of hazardous event/accident.

"BBN is a practical and flexible method that can be used not only in risk analysis, but also in statistics, machine learning and artificial intelligence" (Rausand 2011).

4.5: Method description

Bayesian network in a simple word is a set of direct acyclic graph and table of properties. The graph includes finite number of nodes and related arcs, which present the interrelationship between the nodes. The qualitative feature of the network is presented by the graph and the probabilistic part is used to evaluate the network quantitatively.

Typically, nodes are presented with oval shape or cycle and in some cases with rectangle or diamond shape. Depending on the definition of the nodes, each shape can present a special category of variables such as Chance, Decision, and Utility. Arcs, which illustrate the interrelation between nodes, are arrows with just one direction.

The acyclic attribute of the network means that assuming the three nodes A, B and C, starting from a node to the other nodes following direction of the arcs never ends to the beginning point. In the other word, it is not allowed to have a cycle in the network.

In the BBN each node can have two or more status and value of each status can get a random variable with either discrete or continues distribution. Although number of the nodes are not limited in the model, but the higher number of the nodes the more complexity of the model in term of qualitative and quantitative analysis.

In the BBN model nodes are conditionally independent meaning that the conditional probability of each node given its parents node is only dependent on the probability of the parents of that node. In the other word in case of knowing about the status of parents of a node, knowing about ancestors of the node does not add any information to the knowledge about the status of mentioned node.

BBN illustrates the causal relation between factors that influence a hazardous event. The factors in the model are called Risk Influencing Factors (RIF). Figure 4.1 shows the **BBN** schematically.

Influencing factors are classified to three main categories of Organizational, Human and Technical factors (Rausand 2011).

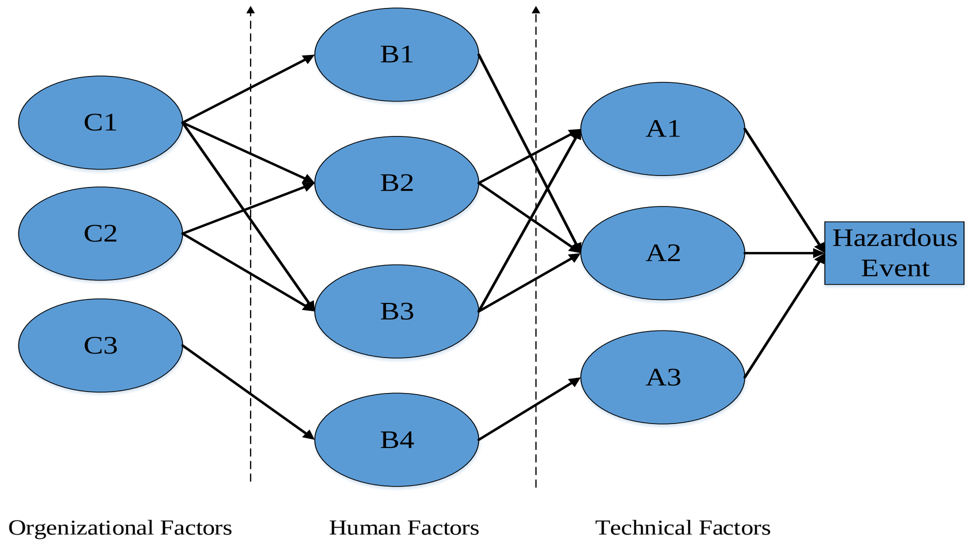


Figure 4.1: Schematic version of BBN adapted from (Rausand 2011)

4.5.1: Variables

In the BBN, sets of mutually exclusive events are presented as significant influencing variables or Risk Influencing Factors (RIF).These set of events can be discrete or continues which the discrete domain is usually finite. In another classification variables can be classified to chance or random variables, decision variables and Utility variables. Chance variables present the random events and the decision variables represent a choice which is under the control of an external actor like human or agent. All three group of variables can be discrete or continues (Kjaerulff 2008).

4.5.2: Causality between variables

Causality has a significant role in constructing the probabilistic networks. When the nodes are defined explicitly in the influencing diagram, the direct link between nodes represents the causal relation between them.

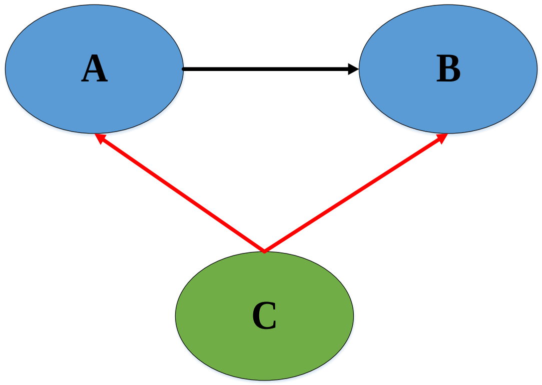


Figure 4.2: Causality between variables

Figure 4.2 illustrates the concept of casualty between variables. The direct link between variables represent the causal relation between two variable.

4.6: Flow of information in the network and categorizing the connections

Because of graphical representation of dependencies, the BBN is called Direct Acyclic Graph (DAG). Serial, Diverging and Converging connections are the most are the three most common connections in the BBN which are explained in the following (Kjaerulff 2008).

- In serial connections having knowledge about status of parents give knowledge about the status of child and vice versa.
- In diverge connections same as serial connections, knowledge about status of parent A gives knowledge about status of child B. But, if we know the status of B knowing about A or C does not change our belief about B.
- In converging connections with no evidence on C, having information about A does not help to update our belief about B.

Figure 4.3 present the three common types of aforementioned connections.

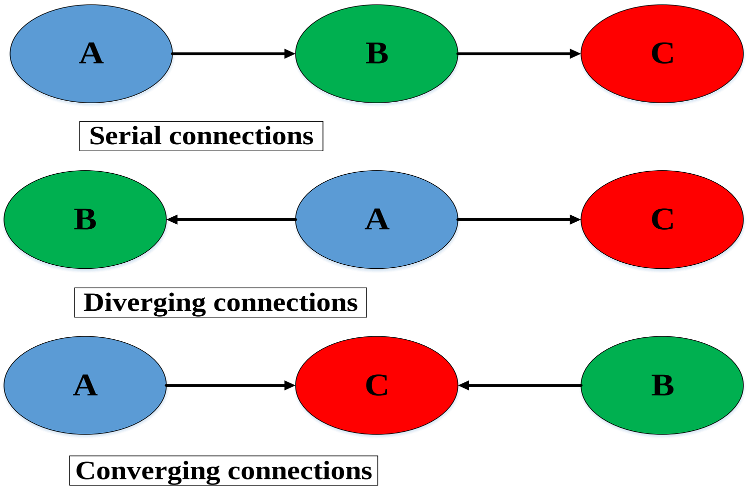


Figure 4.3: Illustration of three types of connections

4.7: conditional probability tables (CPT)

Conditional probability table (CPT) is associated with the likelihood of each state of with every node given the different state of its parent according to previous information or the past experience. In the other word, CPT gives the distribution of variable for each combination of parent node. For example in figure 4.2 node C has no parent, therefor the probability of this node is unconditional but the decedents of C which are A and B are dependent on their respective parents.

With increase in the number of parents and states of each node, the complexity of CPT increases. In the root nodes (C in figure 4.2) which have no parent, the CPT is limited to the list of marginal probabilities of each state of the node (Rausand 2011).

4.8: Construction and analysis of BBN

The probabilistic network can be constructed according to available data and information in a combination of manual and data driven process. The two main aspects of BBN are the structure and the probabilistic parameters. The former one is used in quantitative and the later one is part of quantitative analysis.

The main steps in the construction and analysis of network:

- Identifying the variables in the network.
- Determine the causal or functional relation between variables through an intuitive process in order to identify the directionality of the links in the network and construct the network (parent and child nodes).
- Developing of the conditional probability table for each state of variable given the state of the parent variable(s).
- Analyze the network qualitative and quantitatively

4.8.1: Identification of variables

In the risk analysis, mostly variables are two type of chance or decision, and can be classified to discrete or continues. The risk influencing nodes are identified and this process starts mainly from the end node and then the parent nodes are determined for the end node. The process is continued to the lower level until the desired resolution is fulfilled (Kjaerulff 2008). The variables are mainly three type as following:

4.8.1.1: Problem variables: which are those variables that with having the knowledge about their posterior variables we can make inference about their probabilities.

4.8.1.2: Information variables: these variables are those that information and observation about them is available and are helpful in problem solving.

4.8.1.3: Meditating variables: those variables that their posterior probabilities are not of immediate interest but they have a significant influence on the probability of their childe nodes in the model (the root nodes in the network are among the meditating variables).

4.8.2: Developing the conditional probability network

When all nodes are defined and the arcs are drawn, in the process of assigning the probabilities starts from the root nodes (which do not have any parent) to the end node. The allocated probabilities coms from data analysis, experiment, expert judgment or combination of any of them.

4.8.3: Analysis of the network

I the analysis of the network probability of each state of the nodes are calculated using the conditional probability concept. In most of the real applications due to rather high numbers of conditional probabilities for each node, the calculation is a tedious process. Therefore, use of software is inevitable.

Hugin-Expert and GeNie are among the recommended software's for construction and analysis of BBN which GeNie used for drawing the BBN in this report.

The analysis of network is not only limited to the calculation of probabilities. The analysis consist of determining those factors that have the significant influence on the outcome of the network, which is the value of the end node. This part of analysis consists of Conflict Analysis and Sensitivity Analysis.

4.9: benefits and challenges of using BBN

BBN is accredited for number of merits and criticized for some challenges such as high number of probability parameters in one simple model. Some of the advantages and challenges are named as following (Hänninen 2014):

4.9.1: Advantages

- Suitable for rather complex system.
- Coping with uncertainty.
- Versatility (BBN can be utilized in multiple ways).
- Capability of dynamic modeling (when the state of variables changes over time).
- Can incorporate qualitative and quantitative information (Rausand 2011).
- Has capability of being updated over the time when new information becomes available (Rausand 2011).

4.9.2: Challenges:

- When the number of nodes increases, the workload increases exponentially (Rausand 2011).
- The acyclic feature of BBN can bring limitation when network is used in the field of fire safety. For example, when the actin and performance of fire fighters influences the fire development and the fire development also influences the actin of firefighters acyclic feature of BBN may bring limitation for application (Hanea and Ale 2009). To cope with this limitation adapting dynamic approach can solve the problem (Ghahramani 1997).

4.10: summery

A brief introduction to BBN presented in this chapter. History of BBN and the main features of the model explained and the benefits and challenges using BBN named. The more comprehensive explanation of BBN is given by (Kjaerulff 2008).

Chapter 5

Discussion of the factors and assigned probabilities

According to literature survey, the probabilities of occurrence of the factors that influence uncontrolled fire in machinery space identified in chapter 3. For dome of the factors, the assigned probabilities in the literature were different. This chapter discusses the interrelation between different factors and the most suitable probability/frequency for quantification of the factors. Putting all together results in the completed model for risk analysis of uncontrolled fire, which is presented at the end of this chapter

5.1: Interrelation between factors and the assigned probabilities

5.1.1: Type of ship and the child nodes

Accident statistics has shown that risk of accident is not identical in all ship types. In the suggested BBN model for fire in engine room, ship type introduced as a decision node that is parent of the other organizational or technical factors such as Ship's flag, Class registry of the ship, Age of ship, Maintenance and Safety Culture (Figure 5.1). Type of ship, which has five state in this study (Passenger, Tanker, Container, Bulker and General Cargo) introduced as parent node of age of ship and Class and Flag registry. This does not necessarily mean that change in ship type results in change in class, flag or age of ship.

According to the comprehensive data analysis of world fleet by (Li, Yin and Bang, et al. 2014) (which analyzed of three data sets, analysis of more than 130,000 vessels in the world fleet covering more than 90% of commercial worldwide fleet). If we have data about 90% of the world fleet, with 90% confidence we can determine the probability of being in any of the states of Age, Class or Flag registry by knowing the ship type. Table 5.1 presents the conditional probability of Class registry, Flag and Age of ship given the ship type.

Table 5.1: Conditional probability table for Class, Flag and Age of ship given the ship type (Li, Yin and Bang, et al. 2014)

Factors in model	Status of factor	Dry cargo	Bulk	Container	Tanker	Passenger
Class registry	Non-IACS	81.89	47.80	25.68	53.53	82.27
	IACS	18.11	52.20	74.32	46.47	17.73
Flag registry	Close registered	64.13	34.87	39.52	54.95	80.63
	Open registered	35.87	65.13	60.48	45.05	19.37
Age of ship	New (0-5)	18.76	41.78	43.53	42.10	20.80
	Medium (6-10)	21.13	24.10	16.53	21.56	24.45
	Old (More than 10)	60.11	34.13	39.94	36.35	54.75

Presented probabilities in the table 5.1 are suitable for quantification of BBN model in analysis of fire in engine room.

In the analysis of fire in engine room, level of safety of ship is dependent on two main factors of maintenance and safety culture. In the other world, safety of engine room in terms of fire increases by increasing the quality of maintenance and having excellent safety culture. Likewise, safety of engine room decreases with decrease in quality of maintenance and having poor safety culture. This means that there is a linear relation between quality of maintenance or level of safety culture and level of safety of ship's engine room regarding fire hazard. Influence of ship type on safety culture and maintenance presented in section 5.1.2 and 5.1.3 respectively. Figure 5.1 shows the factors in BBN model that value of them may change in different ship types.

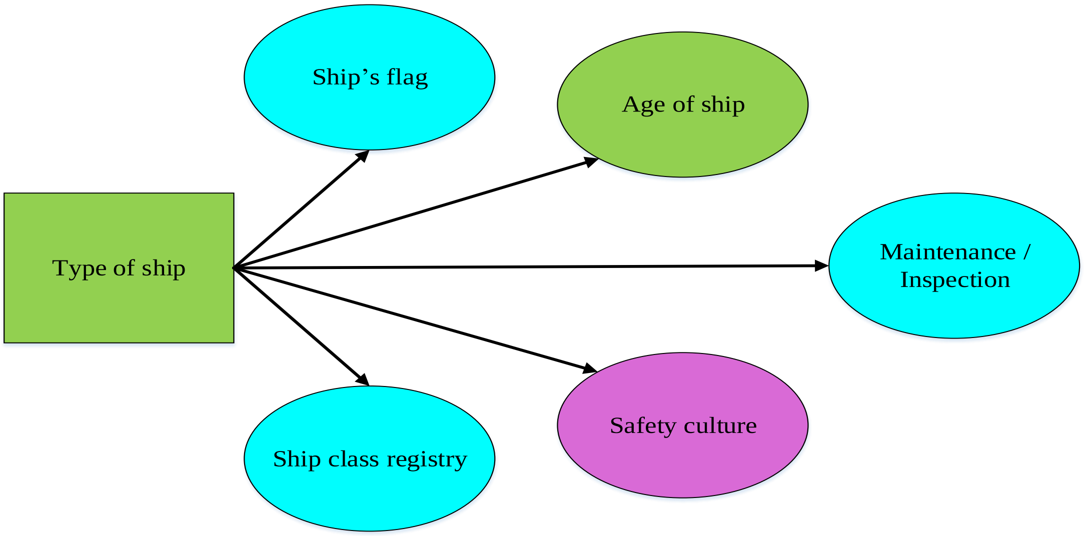


Figure 5.1: Type of ship as parent node and the child nodes in the model.

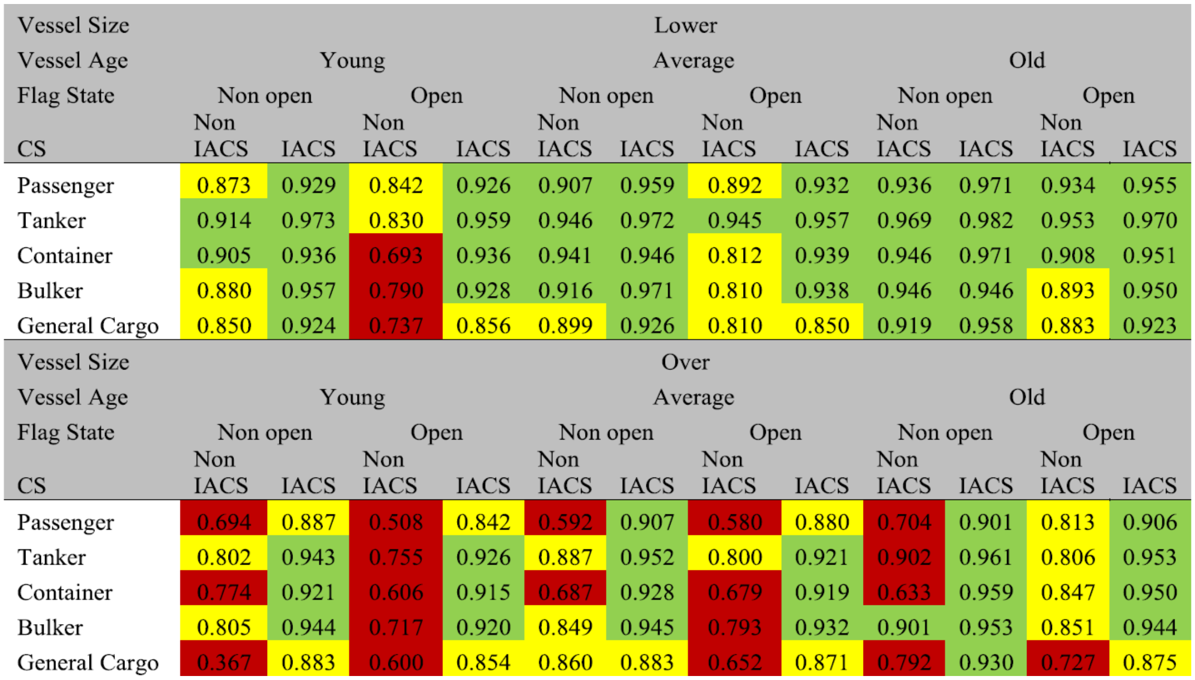
5.1.2: Safety Culture and the parent nodes

Whenever human, directly or indirectly, associates with any type of accident, safety culture becomes one of the influencing factors in risk analysis. Method of evaluating the safety culture is not straightforward and unique. Depend on how safety culture is defined, different approached can be adapted to evaluate the safety culture in the industry and different approached would give different result.

In the study of influencing factors in safety culture, 40-item safety culture questionnaires developed and distributed among a group of 349 officers and sailors. Result confirmed that factors such as occupation, nation and vessel types had significant influence in the result of analysis (Håvold 2005). In line with this study safety culture analyzed onboard on 63 Norwegian-owned tankers. Analysis of 1158 questionnaires in the study (which collected from 63 tankers) showed that, ship owners, sailors' occupation, sailors' country of origin, sailors' age, ship flag, class registration and age of vessels influenced the response of seafarers to the questionnaires (Håvold 2010).

Accident statistics has shown that, influences of some factors (e.g. ship type, ship flag-open/close registry-, classification society etc.) on accident frequency and safety level of ships are not identical in all types of vessels. It can be concluded that, the aforementioned influencing factors have influence in safety culture, which consequently results in increase or decrease in general safety level of ship. In the study of ship safety index, based on comprehensive analysis of observing more than 90% of world fleet, safety level of ship determined according to different factors influencing the safety level (Li, Yin and Fan 2014). In this study, safety level (Index) of ship defined as an index that developed through parameterizing an exponential function of the vessels operating characteristics. In the result of equation, safety index of ship fell in the range of [0, 1]. The higher value of safety index, the better ships safety level. Figures presented in a table with three colors of Green, Yellow and Read for more intuitive understanding of figures (Index). The index of above 0.9 defined as safe (Green), between 0.8 and 0.9 considered standard (Yellow) and below 0.8 assumed as risky (Red) (Li, Yin and Fan 2014). Table 5.2 presents the conditional probability table of safety level (Index) in different categories of vessels according to different factors. (In table 5.2, age ≤ 5 years regarded as young, between 6 to 10 years considered average and above 10, defined old).

Table 5.2: safety level of different ship groups depend of different factors (Li, Yin and Fan 2014)



Vessel Size	Lower											
Vessel Age	Young				Average				Old			
Flag State	Non open		Open		Non open		Open		Non open		Open	
CS	Non IACS	IACS	Non IACS	IACS	Non IACS	IACS	Non IACS	IACS	Non IACS	IACS	Non IACS	IACS
Passenger	0.873	0.929	0.842	0.926	0.907	0.959	0.892	0.932	0.936	0.971	0.934	0.955
Tanker	0.914	0.973	0.830	0.959	0.946	0.972	0.945	0.957	0.969	0.982	0.953	0.970
Container	0.905	0.936	0.693	0.936	0.941	0.946	0.812	0.939	0.946	0.971	0.908	0.951
Bulker	0.880	0.957	0.790	0.928	0.916	0.971	0.810	0.938	0.946	0.946	0.893	0.950
General Cargo	0.850	0.924	0.737	0.856	0.899	0.926	0.810	0.850	0.919	0.958	0.883	0.923

Vessel Size	Over											
Vessel Age	Young				Average				Old			
Flag State	Non open		Open		Non open		Open		Non open		Open	
CS	Non IACS	IACS	Non IACS	IACS	Non IACS	IACS	Non IACS	IACS	Non IACS	IACS	Non IACS	IACS
Passenger	0.694	0.887	0.508	0.842	0.592	0.907	0.580	0.880	0.704	0.901	0.813	0.906
Tanker	0.802	0.943	0.755	0.926	0.887	0.952	0.800	0.921	0.902	0.961	0.806	0.953
Container	0.774	0.921	0.606	0.915	0.687	0.928	0.679	0.919	0.633	0.959	0.847	0.950
Bulker	0.805	0.944	0.717	0.920	0.849	0.945	0.793	0.932	0.901	0.953	0.851	0.944
General Cargo	0.367	0.883	0.600	0.854	0.860	0.883	0.652	0.871	0.792	0.930	0.727	0.875

Section 3.2.8 in chapter 3 presented quantified values of safety culture based on different studies. The conditional probability table for safety culture presented in table 3.7. Safety culture classified to three states of excellent, standard and poor according to different types of ship. In the BBN model for engine room fire, safety culture is child node of five parents. Change in the state of any of the parents may result in change in the value of safety culture. Type of ship is a decision node, which gets a set of discrete stats of ship type and discussed earlier in section 5.1.1.

Ship age is a continues variable, but changed to discrete variable by introducing three status of young (0-5), average (6-10) and old (over 10). Effect of aging on the safety of vessel is a controversial factor in the literature review. In section 3.2.9, effect of ship's age on safety of ship presented in more details. In analysis of risk of fire, safety of ship cannot be inferred by knowing the ship age because safety of ship is more dependent on quality and maintenance of technical equipment. The most comprehensive analysis of database by (Li, Yin and Fan 2014) showed that ship age has no negative impact on ship safety. Because when fire in engine room is concerned, reliability of equipment is more influenced by maintenance than aging (See table 5.1).

Class registry of ships introduced as one of the parent nodes of safety culture and discussed in section 3.2.3 in chapter 3. Reports of statistical analysis of accident data in all literatures presented that vessels that registered in IACS members were less subject to accident in comparison with vessel under classification of Non-IACS members (See table 5.1).

Ship flag registry as another parent node of safety culture discussed in 3.2.6. In the most of accident studies, flag registry of ship classified in either Gray, Black and White or Open/Close registry. Upon the literature review, study of ship safety index (Li, Yin and Fan 2014) and analyzed the most comprehensive accident data. In this study, flag of ships classified to Open/Close registry. This study showed that close registered ships are safer than open registered ships. Because in the study of ship safety index, accident data was very comprehensive (covering 90% of world fleet), result of Open/closed registry adapted for quantification of ship's flag in this study (See table 5.1).

Deficient training also introduced as a parent node for safety culture. In evaluation of training, there is a need for explicit definition of training. In marine or offshore industry, there is a standard for training of all skills. All seafarers and crewmembers who serve on board on ship or offshore rigs must go through the needful training courses in compliance with Standard of Training and

Watch keeping Certificate (STCW) regulated and approved by IMO. In section 3.2.2, based on offshore accident database and reported data by HSE (HSE 2005), probability of deficient training (5%) presented for use in BBN. Because in marine and offshore industry, all the staff are trained for firefighting according to the same standard, the probability of deficient training in section 3.2.2 (0.05) adapted for quantification of training node in this study.

In analysis of ship risk index, increase in safety culture results in increases safety level of the ships, which represents safer engine room regarding fire accident. Therefore, in determining conditional probability table for safety culture in the BBN model, the conditional probabilities in table 5.2 (safety level/index of ship) may be used for weighing of parent nodes of safety culture in the model. Although a degree of expert judgment is needed for determining the conditional probabilities. Figure 5.2 present the relation of safety culture and the suggested parent nodes in the model.

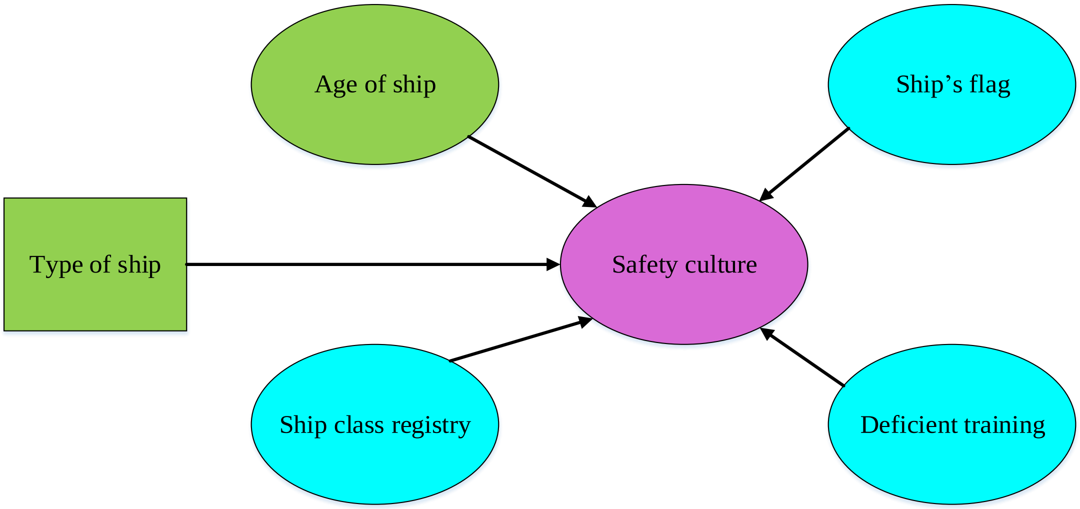


Figure 5.2: Safety culture and parent nodes in BBN model

5.1.3: Maintenance/Inspection and parent nodes

Upon the literature survey, no record of any evidence found regarding analysis of level of maintenance in vessels in the accident data. The reason is due to the fact that, there is a typical format for reporting of accidents in which, the reason of accident, specification of vessels and general information are reported. Therefore, level of maintenance in risk analysis is more quantified by expert judgment. An alternative approach for evaluation of maintenance is using estimated cost (investment) in maintenance (for different ship types, size and age) and applying the suggested measures for evaluation of maintenance which presented in section 3.2.1. For quantification of maintenance in BBN model for this study, the most appropriate figures for maintenance in literature survey were the values of maintenance depending on safety culture by (Hänninen and Kujala 2012). Result of formal safety assessment (DNV 2006) plus expert judgment used for quantification of maintenance by (Hänninen and Kujala 2012) and result adapted for quantification of maintenance in this study. In this study maintenance classified to "Good" and "Poor" depending on status of safety culture in ship. Conditional probability table of maintenance given different status of safety culture presented in table 3.7. In addition to safety culture, Age of ship, Type of ship, Ship Flag registry and Class registry of ship also introduced as parent nodes of maintenance.

Obviously improving the maintenance of ship increases the safety level of engine room regarding risk of fire. Therefore, high level of safety (in terms of fire) in ship implies good level of maintenance. Safety level of ship analyzed in the study of ship safety index. Ship's age, class registry, ship flag and type of ship introduced as influencing factors in calculation of ship safety level (index). These factors are identical to the parent nodes for maintenance. Therefore, the figures in the conditional probability table of ship safety level given the influencing factors (table 5.2) can be used for weighting the parent nodes of maintenance in figure 5.3 (in order to develop the conditional probability table in BBN). Although developing the conditional probability table of maintenance for the given parent nodes (figure 5.3), needs a degree of expert judgment.

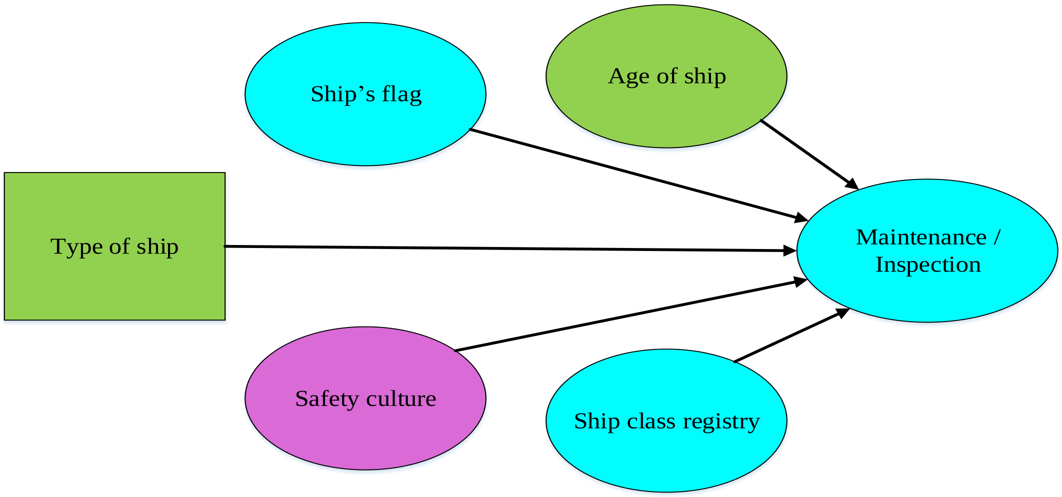


Figure 5.3: safety culture as a parent node of maintenance

5.1.4: Child nodes of maintenance

Maintenance is one of the important factors that can influence many other factors in the model. Figure 5.4 shows the factors that are subject to change if the status of maintenance changes in the model. Probability of leakage in different locations will be discussed later in this chapter. Probability of detection of fire discussed in section 3.2.14 and according to the literature review the probability of 1% calculated to be the average probability for the whole detection system including detectors, logic solver and fire alarm. Probability of failure on demand for fire pump (PFD= 0.0264) discussed in section 3.2.13 calculated according to Reliability Block Diagram (RBD) in figure 3.8 based on reliability data from OREDA handbook. Probability of failure in fire damper system calculated with using RBD in section 3.2.12 and presented to be: (PFD= 0.0041). Probability of failure for quick closing valve system discussed in section 3.2.15 and presented to be (PFD=0.00074). The presented numbers are the average failure probability for mentioned systems in normal (Standard) condition. Status of maintenance (Poor maintenance) can increase the failure probability of safety systems. Developing conditional probability of child nodes of maintenance in figure 5.4 need a degree of expert judgment.

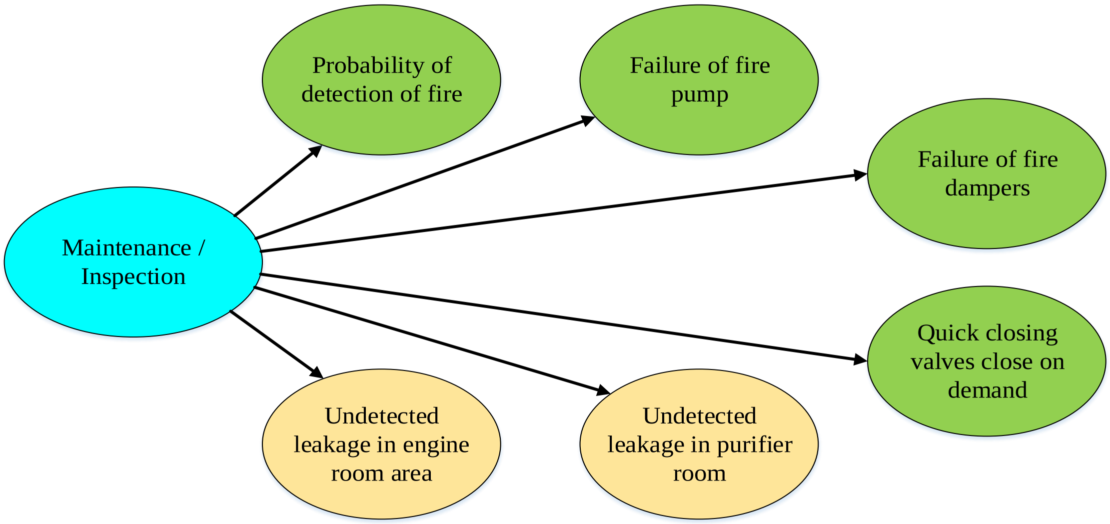


Figure 5.4: Child nodes of Maintenance/Inspection in the model

5.1.5: Leakage in engine room and the influencing factors

Undetected leakage is the initiation hazardous event that may lead to fire, if hydrocarbon contacts to a hot spot or ignition source. Probability of leakage in pipeline and machinery presented with equations in most of published articles. In the literature survey, no evidence found in any estimation of probability/frequency directly by use of accident data. Probability of leakage in different locations of engine room quantified in section 3.2.18 using the equation introduced by (Emi, et al. 1997) (See table 3.13). Although the article is rather old, but the design and technology of piping, flanges, connections and joints has not changed significantly since 1997. Most of changes and advancement in technical systems in the last two decade has been in automation and improving the efficiency and performance of machinery. Therefore, the suggested equation is still reliable to for estimating the probability of leakage in engine room. Figure 5.3 presents the factors that influence the frequency of leakage in engine room. Purifier room presented in separate node in the model because purifier room is a separated compartment with dedicated fixed firefighting system. Leakage in engine room area gets six state (leakage in: Main engine, Diesel generator, Boiler, Incinerator, Other sources). In addition to maintenance, which influences the probability of leakage, sailing status of ship (in sailing/stop) can also determine the probability of leakage associated with machinery under operation. For example, main engine is running and boiler is stopped while sailing and in contract, when ship is stopped main engine is stopped and boiler is running. Incinerator can be operated just when ship is in sailing and at least 12 nautical mile away from the land. According to the statistical data presented in section 3.2.16, vessels showed more prune to fire in sailing condition than in stopped position. Analysis of fire accident reports in table 3.10 and 3.11 presents that status of ships classified in port and non-port accidents. When ship is in port, ship is stopped. In non-port situation, ship assumed to be in sailing or drifting. Figure 5.5 presents the relation of leakage and influencing (parent) factors in the BBN model. Developing the conditional probability table for leakage, given the different status of maintenance (parent node) needs a degree of expert judgment.

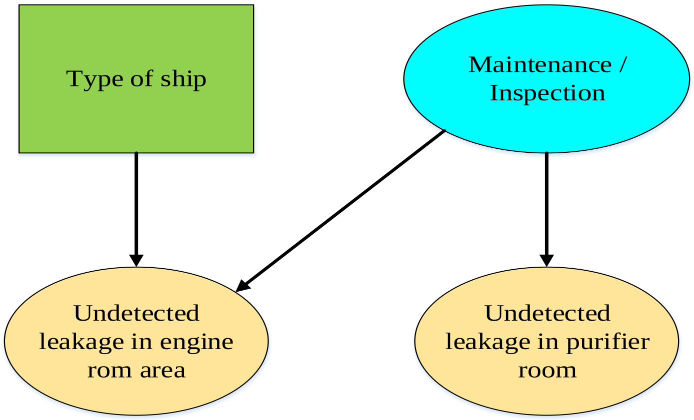


Figure 5.5: Leakage in engine room and the parent nodes

5.1.6: Start of fire and influencing parents

Start of a fire initiates upon occurrence of leakage and contact of hydrocarbon to the source of energy (ignition). Review of literature in probability of ignition in section 3.2.19 showed that probability of ignition is function of temperature of inflammable hydrocarbon, density of hot spot in the area and type of ignition source. Two different approach introduced for calculation of probability of ignition and probability of ignition calculated according to the two different equations. Table 3.15 presented the probabilities of ignition according to the equation formulated for offshore process industry developed by (PULA, et al. 2006). Table 3.18 presented the probability of ignition in engine room in different location according to mean value of distance between leakage and ignition source. Comparison of two table showed significant difference in the calculated probabilities. One reason of getting higher probabilities in table 3.15 might be due to parameter of release-time (about 2 hours) that applied in equation for calculation of ignition probability. Considering different approaches in section 3.2.19 for calculation of probability of ignition, figures in table 3.18 were more suitable for use in the model. Because the equation by (Emi, et al. 1997) formulated specifically for fire in engine room. Starting a fire as an immediate node for uncontrolled fire in engine room gets three states (fire in engine room area, fire in purifier room and no-fire). For developing conditional probability table in probability/frequency of starting a fire, probability/frequency of leakage in any specific area needs to be multiplied by probability of ignition in the corresponding location. General equation for calculation of this conditional probability table discussed in section 3.2.20. Figure 5.6 presents starting a fire as the event triggering the accident and the parent nods for it in the model.

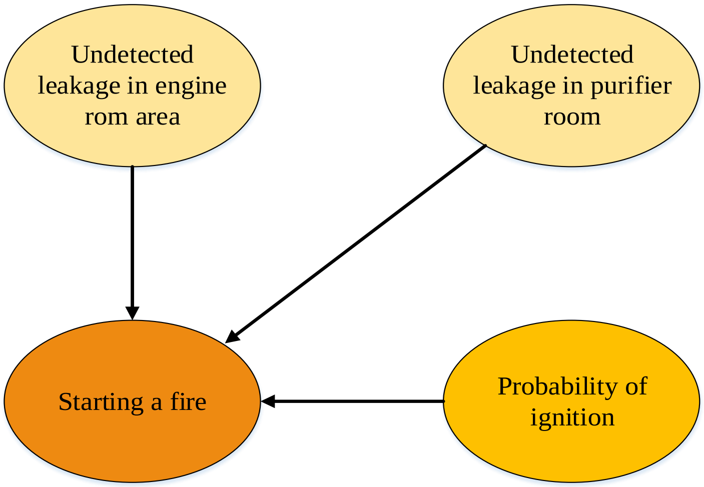


Figure 5.6: Starting a fire and parent nodes

5.1.7: Probability of detection of fire and the child nodes

Probability of detection of fire discussed in section 3.2.14 and calculated to be 99% on average. Hyper mist system, quick closing valves, fire dampers, high expansion foam system and proper action on time are dependent on the detection of fire. The technical barriers are activated manually or automatically upon the detection of fire. Timely action of staff is also dependent on the on time notification of fire. According to the literature review in chapter 3, the basic probability of any of the child events are as following:

Failure of fire dampers = 0.0041(section 3.2.12) , failure of high expansion foam system= 0.0252 (section 3.2.11), failure of hyper mist water sprinkler system= 0.036 (section 3.2.10), probability of failure of quick closing valves= 0.000742 and probability of proper action on time = 0.708 (section 3.2.7). Figure 5.7 presents the correlation between probability of detection of fire and the aforementioned child nodes. As discussed earlier the mentioned probabilities are the basic probabilities and developing the conditional probability table for each factor given the state of parents needs a degree of expert judgment, which presented in the further work at chapter 7.

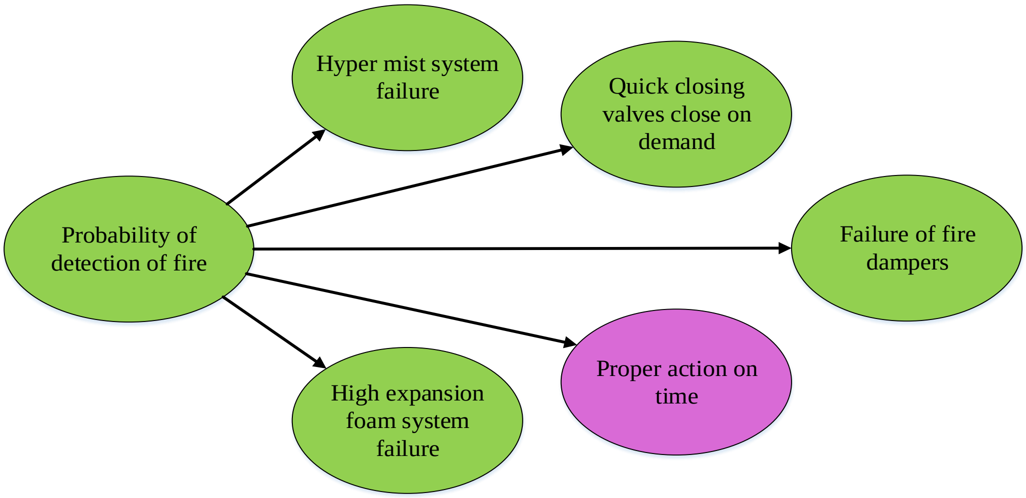


Figure 5.7: probability of detection of fire and child nodes

5.1.8: Timely action

Proper action on time presented as child node of deficient training, not complying with the instruction, inefficient emergency plan and probability of detection of fire. Training and emergency plan have a standard in offshore and marine industry. All the regulation regarding emergency plan and training documented in ISM and SOLAS, which enforced by IMO. Probability of having insufficient emergency plan and not complying with the instruction estimated to be 0.05 and 0.2 respectively and presented in and 3.2.4. Probability of deficient training calculated to be

0.05 in section 3.2.2. Probability of detection of fire also discussed in section 3.2.14. The mean probability of proper action on time presented in figure 3.3 according to suggested BBN model for offshore fire/explosion, in analysis of human and organizational factors involved in fire prevention. Review of data in literatures for action on time presented in section 3.2.7. Conditional probability table of proper action on time given the parent nodes need a degree of expert judgment in further analysis of model. Relation between on time action and the influencing parent nodes presented in figure 5.8.

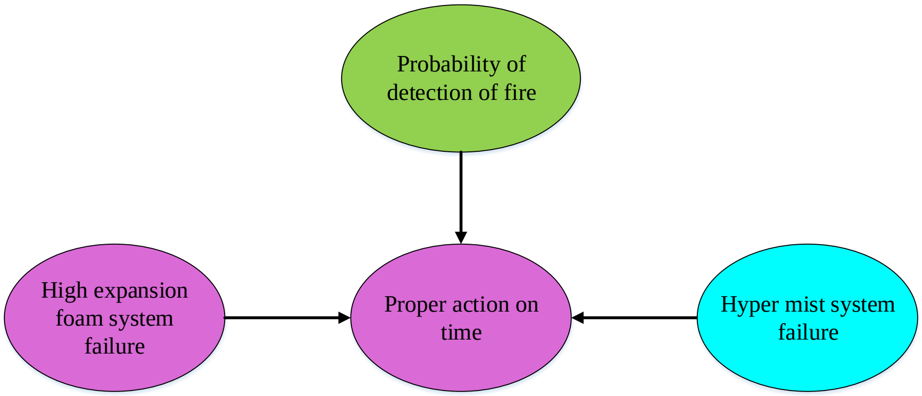


Figure 5.8: Proper action on time in case on contingency and the parent nodes in the model

5.1.9: Manual fire suppression and the influencing factors

Manual suppression of fire is one of the measures to control the fire. In firefighting operation normally in each group, two firefighters equipped with firefighting outfit attack the fire. Probability of failure to suppress the fire by one group of firefighters (as presented in table 3.6) depends on the scale of fire and ability of firefighters. The probability of failure presented for average area of $37.16\ m^2$ in section 3.2.7. Crewmembers onboard on vessels are trained for firefighting, but their profession is not firefighting. Therefore, seafarers considered as average trained for firefighting operation. Proper action on time is the parent node that can influence probability of manual fire suppression by personnel. In case of failure of emergency fire pump firefighting cannot be carried out. On-time action of crew introduced as parent node of manual suppression failure and discussed earlier in this chapter. Probability of failure in emergency fire pump calculated in section 3.2.13 according to OREDA handbook ($PFD_{Total-Avg} = 0.0264$). Figure 5.9 presents the parent nodes of manual suppression in the model.

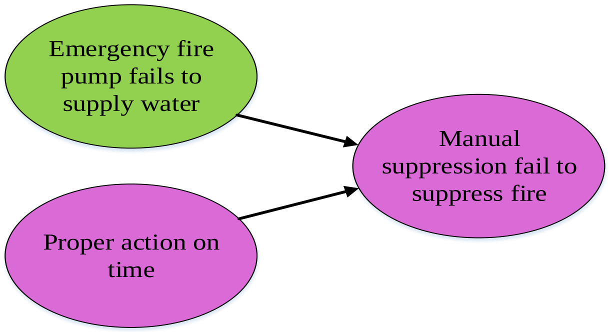


Figure 5.9: Influencing nodes in manual suppression of fire

5.1.10: High expansion foam failure and the parent nodes

High expansion foam system introduced as a barrier for fire development in engine room. This fixed system is used in purifier room (and pump room in tankers) for intense fire extinguishment. The system manually or automatically activates to release the foam in the designated area upon the detection of fire. Therefore, if the fire remains undetected the system also remains deactivated. Probability of detection of fire discussed in detail in section 3.2.14 ($PFD_{fire\,detection\ system} = 0.01015$). In all onshore, offshore and marine applications the same technology and design is used for installation of foam system. Probability of failure on demand of system calculated in section 3.2.11($PFD_{Foam\ system} = 0.0252$). Foam system needs sea water supply for functioning. Failure in emergency fire pump trigger cascading failure in high expansion foam system (section 3.2.13). Obligation on use of fixed fire extinguishing system amended to SOLAS in 2002 (section 3.2.5). Vessels built before July-2002 were not obliged to have the fixed high expansion foam system installed. Complying with the new regulation determines whether high expansion system is installed onboard of vessel or not. Figure 5.10 presents the relation of high expansion foam system as a barrier and parent nods of this barrier in the BBN model.

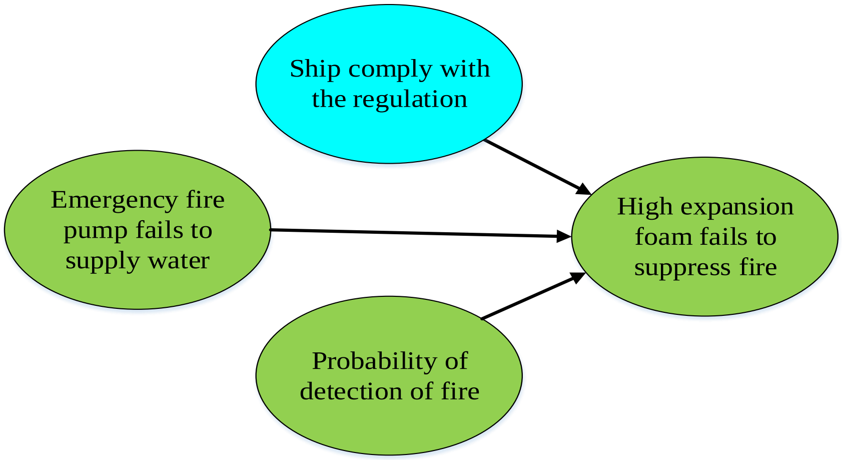


Figure 5.10: Failure of high expansion foam system and influencing parent nodes

5.1.11: Hyper-mist / Sprinkler system and the parent nodes in the model

Hyper-Mist (water sprinkler) system is a fixed fire extinguishing system, which in addition to having the cooling effect, displaces the oxygen in the area and causes smothering the fire. The system activates automatically / manually upon the detection of fire (probability of detection discussed earlier in this chapter). Similar to high expansion foam system, use of this system enforced after 2002 in new amendment of SOLAS. Therefore, complying with the new regulation determines if the vessel is equipped with the fixed sprinkler (Hyper-Mist) fire extinguishing system or not. Probability of failure of fixed sprinkler system discussed in more detailed in section 3.2.10. According to the literature review and calculation of PFD for complete system, average $PFD_{water\ mist} = 0.036$ considered to be an acceptable value for probability of failure in the analysis of BBN model. Figure 5.11 shows water sprinkler system in the model and the influencing parent nodes in the probabilistic network.

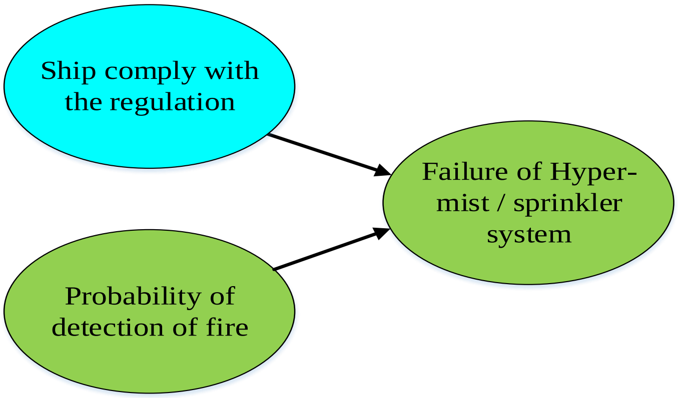


Figure 5.11: Relation between failure of Hyper Mist system and the parent nodes in BBN

5.1.12: Uncontrolled fire in engine room and the parent factors

Developed/Uncontrolled fire is the outcome node of BBN model. The developed/uncontrolled fire in engine room occurs when fire starts in a compartment and barriers fail to suppress the fire. Figure 5.12 presents the immediate contributing factors in occurrence of uncontrolled fire in the suggested BBN model for fire in engine room. Developing the conditional probability of uncontrolled fire given the states of parent nodes may need a degree of expert judgment in the further analysis of model.

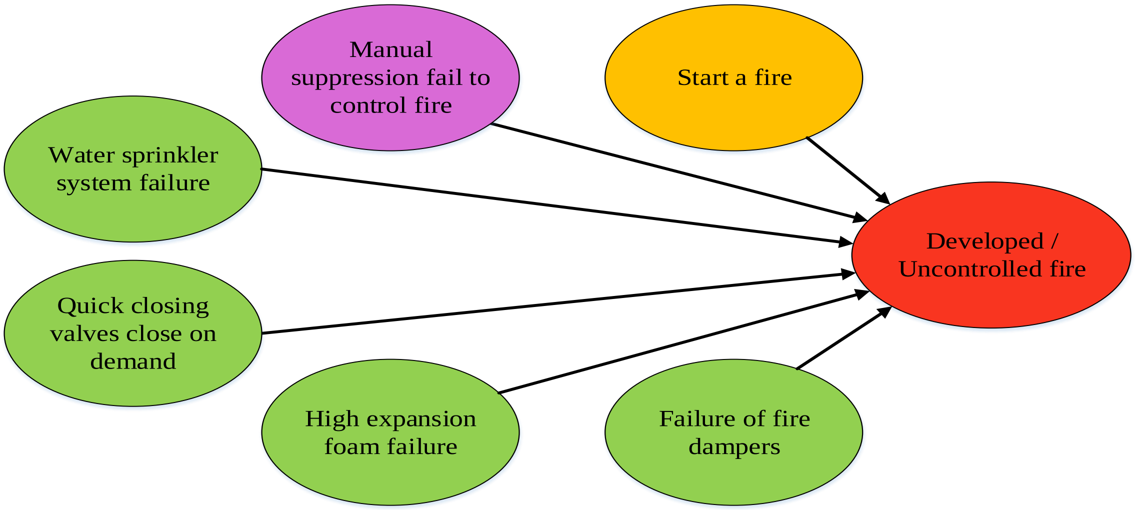


Figure 5.12: Immediate factors influencing probability of Developed/Uncontrolled fire

5.2: Necessity of analysis of AIS data for quantification of model

The suggested BBN model is a rather general model that can be used for analysis of fire in engine room in any position of ship. However, some parameters in the model are dependent on Automatic Identification System (AIS) data in the location of analysis. Use of AIS data makes the model rather unique for analysis of fire in the specific region. In the following, the factors, that are dependent on AIS data, are presented and discussed.

5.2.1: Type of ship (Node-19)

As discussed earlier, type of ship presented as parent node of safety culture. This factor presented as a decision node in the model. The states of decision node gets discrete values (Which are types of ship in this case such as Tanker, Bulk carrier etc.). The factor of ship type might be analyzed in form of a chance node in the model instead. For quantifying the ship type as a chance node, AIS data needs to be analyzed to calculate, out of all vessels that sail in the specific region (Norwegian waters) in one year, what proportion/percentage of them are of any specific ship type of ship (Tanker or passenger ship for instance).

5.2.2: Ship in sailing or stopped (Node-18)

Movement status of ship determines whether or not some of machineries such as main engine of ship are working. This node can be quantified by analyzing the AIS data. For quantification of this factor using AIS data. Duration of time that ships are in sailing in the selected region (Norwegian waters) over the whole time that ships are in that region is a figure that can be calculated through analysis of AIS data.

5.3: BBN model for uncontrolled fire in engine room

Considering all the influencing factors and the interrelation between them, the BBN model for uncontrolled fire developed in figure 5.13. List of the nodes and parent nodes and the corresponding probabilities and reference of assigned data presented in table 5.3.

Table 5.3: Table of Correlation between nods in BBN

Category	ID	Name of Node	Parent Node(s)	States	Reference for probabilities
Organizational Factors	1	Maintenance/Inspection Efficiency	3,6,9,11, 19	Good / Poor	Table 3.2
	2	Deficient training		Yes = 0.05 / No =0.95	Section 3.2.2
	3	Ship class registry	19	IACS / Non-AICS	Table 3.4
	4	Insufficient Emergency Plan	9	Yes = 0.05 No =0.95	Section 3.2.4
	5	Ship comply with new regulation	11	Yes / No	Section 3.2.5
	6	Ships flag	19	Open / Close registered	Table 3.5
Human Factors	7	Proper action on time	2,4,8,16	Yes =0.708 / No= 0.292	Section 3.2.7
	8	Not Comply with instruction	9	Yes = 0.2 No =0.8	Section 3.2.4
	9	Safety culture	2,3,6,11, 19	Excellent / Standard / Poor	Section 3.2.8 Table 3.7
	10	Manual suppression fail to control fire	7,15	Yes= 0.02995 No= 0.97005	Table 3.6
Technology Factors	11	Age of ship	19	New / Medium / Old	Table 3.8
	12	Hyper mist system failure	5,16	Yes= 0.036 No= 0.964	Section 3.2.10
	13	High expansion foam system fail to suppress fire	5,15,16	Yes= 0.0252 No= 0.9748	Section 3.2.11
	14	Failure of fire damper	1,16	Yes= 0.0041 / No= 0.9959	Section 3.2.12

	ID	Name of Node	Parent Node(s)	States	Reference for probabilities
	15	Emergency fire pump fail to supply water	1	Yes= 0.0264 No= 0.9736	Section 3.2.13
	16	Probability of detection of fire	1	Yes= 0.98985 No= 0.01015	Section 3.2.12
	17	Quick closing valves close on demand	1,16	Yes = 0.999206 No = 0.0007942	Section 3.2.15
	18	Ship in sailing/stop		In sailing / Stopped (Decision node)	Section 3.2.16
	19	Type of ship		Dry cargo/ Bulk/ Tanker/ Container/ Passenger	Section 3.2.17
Immediate Factors	20	Undetected leakage in purifier room	1	Yes= 0.0303 No= 0.9697	Table 3.13
	21	Undetected leakage in engine room area	1,18	Boiler / Incinerator / Main Engine / Diesel Generator / Other Sources / No leakage	Table 3.13
	22	Probability of having ignition		Boiler / Incinerator / Diesel Generator / Main Engine / Purifier room / Other Sources / No ignition	Section 3.2.19 Table 3.18
	23	Starting a fire	20,21,22	In Purifier room / In Engine room area / No fire	Section 3.2.20
	24	Developed uncontrolled fire	10,12,13,14,17,23	Yes No	

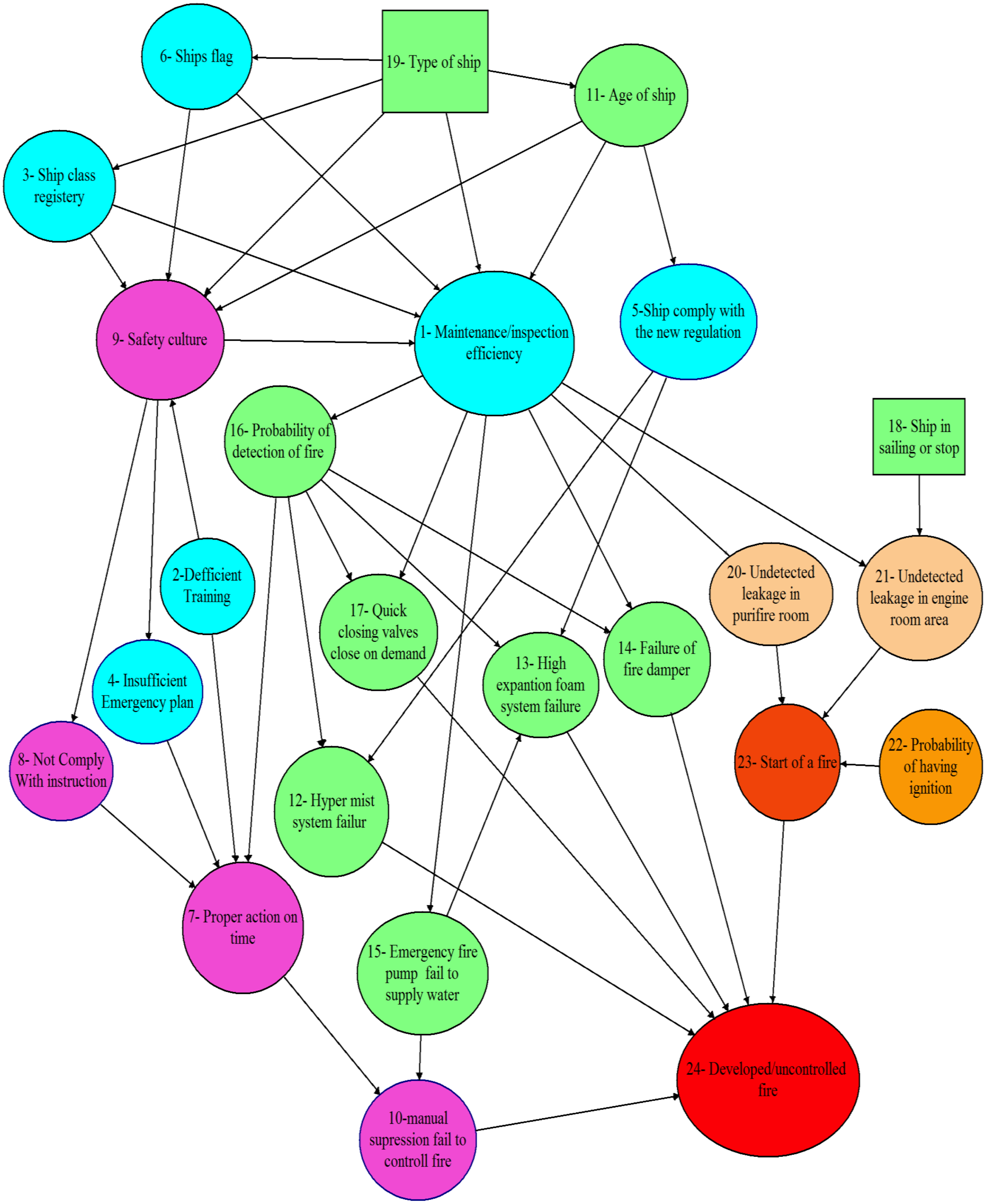


Figure 5.13: Bayeian Belief Network for fire in engin room

Chapter 6

Conclusion

In this report, the statistical data regarding fire in the ship reviewed in chapter two, which showed fire has a big share in the ship accident and risk of maritime transport. Despite the improvement in regulations both in operation and design of vessels, still frequency of fire in the vessels (engine room) is considerable. The revision of international standards has been based on a reactive approach rather than having a proactive approach. The literature survey showed that risk analysis of fire in engine room has not been subject of research in the recent years. Although some attempts led to publishing couple of articles with the title of fire in engine room, but the content of the articles does not address the risk influencing factors or risk modeling of uncontrolled fire in ship's engine room. Identifying the influencing factors for uncontrolled fire in machinery space and developing a proactive risk model can help better understanding and analysis of fire in engine room of the vessels, which may result in updating the standards and regulation accordingly. For the suggested BBN in this study, the main assumption for identification of factors in the model was according to general features of a standard engine room. Therefore, the model can be used for analysis of fire in engine room of vessels in any region of the world. In this report, the risk influencing factors associated with uncontrolled fire in machinery space identified for building the risk model using BBN. In quantification process of risk influencing factors, direct analysis of databases could be an option, but due to limited access to databases, the process constrained to surveying published literatures for gathering the suitable quantitative data for the factors in the model. Chapter 3 presented the basic probabilities assigned to the risk influencing factors using literature survey. Chapter 4 introduced the BBN methodology. Chapter 5 discussed the relation between the influencing factors and the suitable assigned probabilities for quantification of the factors. In order to analyze the risk of uncontrolled fire in machinery space for a specific region, statistical record on sailing of different vessels is needed. Analyzing the records of AIS data can give the estimation for proportion of sailing of any type of ship to the all vessels in that specific region. Status of ship (In sailing / stopped) is associated with the number and type of running machineries, which consequently influences the probability of leakage in various parts of engine room. The average proportion of the time being in sailing in the region of interest to the whole time of being the region for all ships, gives the quantitative input to the factor of ship sailing status (in Sailing / Sopped) in the model. In the suggested BBN model, factors of Ship in Sailing/Stopped and Type of Ship need input from analysis of AIS data for getting appropriate result to the region of interest. Using the AIS data for the two aforementioned nodes results changing the type of nodes from decision to chance node (see section 5.2). Weights of parents of each factor needs to be determined using expert judgment.

Once the weights identified, the conditional probability table can be developed and the model can be analyzed. An analytical approach for weighting the parent nodes (Analytical Hierarchy Process) and a semi mechanistic procedure using the weights introduced for developing the conditional probability tables (CPT) in the further work (chapter 7).

Chapter 7

Further work

In order to analysis the BBN model knowing the inherent probability of any of the nodes based on literature survey is helpful but not enough. In the BBN, many of the nodes have one or more than one parent. In order to determine the change in the probability of each stat of any node given the change in the state of its parent(s) the conditional probability table needs to be developed for each node given the different states of its parent(s). One of the main challenges in the quantitative analysis of BBN is developing the conditional probability table for the factors (nodes) in the BBN model. Specially, when number of the nodes increases the number of conditional probabilities increases exponentially which result in time consuming and rather complicated work. Although some software programs are designed to perform the calculation. Assigning each single conditional probability to the CPT for all nodes in the model needs a degree of estimation by an expert or group of experts.

Another challenge in the quantification of BBN is that, degree of influence on child node among the prents is not identical. In the other word, some of the parent nodes may cause bigger change in the probability of state of their child node in compare with their counterparts for the corresponding child. It means that if any node gets more than one parent in the BBN model, the weight of the parents are not necessarily similar. In the quantification process of BBN, determining the weights of the nodes is the essential step in developing the conditional probability tables. Determining the weights for nodes in BBN is an intuitive process by experts usually with the using of statistical data if available. Once the weights are determined, the conditional probability table is developed for each node.

7.1: Weighting the parent nodes in the model

Analytical Hierarchy Process (AHP), introduced by Thomas Saaty (1980) is an effective tool to deal with complex decision making. Determine the weights of different influencing criteria in the decision making process is the first step in the AHP which can be adapted for weighting of the each set of parent nodes in the BBN model. The method generates a weight for each influencing factor (node) according to decision maker's pairwise comparison of the factors. The method is very flexible and powerful because the weights are obtained on the basis of pairwise relative evaluation of the factors using both result from data (if available) and the expert's opinion.

In order to determine weights of the odes using AHP method, the first step is creating a pairwise comparison matrix (A). The matrix is a $m \times m$ real matric where m number of influencing factors considered. Each entry a_{jk} of matrix A represents the importance of the jth factor in comparison with kth factor. If $a_{jk} > 1$ then the jth factor is more important than the kth factor. In the similar way if $a_{jk} < 1$ the importance of jth factor is less than the kth factor. If both factors of j and k have the same importance then $a_{jk} = 1$. Obviously, $a_{jj} = 1$ for all j. The following constraint must be fulfilled in the matrix (Saaty 2004):

$$a_{jk} \times a_{kj} = 1 \Leftrightarrow a_{jk} = \frac{1}{a_{kj}}$$

With assigning a numerical scale from 1 to 9, the relative importance between two nodes are measured. Experts are asked to give all the weighting numbers in the pairwise comparison of nodes according to the table 6.1. It is also possible to assign intermediate values, which may not correspond to the precise interpretation.

Table 6.1: the fundamental scale of absolute numbers for pairwise waiting of factors in AHP (Saaty 2008)

Importance	**Definition**	**Explanation**
1	Equal Importance	Two factors contribute equally to the subject
2	Weak or slight	
3	Moderate importance	Experience and adjustment slightly favor one factor over another
4	Moderate plus	
5	Strong importance	Experience and adjustment slightly favor one factor over another
6	Strong plus	
7	Very strong or demonstrated importance	One factor is favored over another; its dominance demonstrated in practice
8	Very, very strong	
9	Extreme importance	The evidence favoring one factor over another is of the highest possible order of affirmation
Reciprocals of above	If activity i has one of the above non-zero numbers	A reasonable assumption
1.1-1.9	If the importance of factors are very close	May be difficult to assign the best value but when compared with the other contrasting nodes the size of the small numbers would not be too noticeable, yet they can still indicate the relative importance of the activities.

By weightings that we give to the experts according to their experience, education etc. the mean number is derived for each set of pairwise comparisons in the matrix.

When the matrix A is developed, the normalized pairwise comparison matrix A_{norm} is created by making sum of entries of each column equal to one. Where for each entry $\overline{a}_{jk}$ of the matrix, A_{norm} is computed as following:

$$\overline{a}_{jk} = \frac{a_{jk}}{\sum_{l=1}^{m} a_{lk}}$$

The weight factor w (which is an $m - dimentional$ column vector) is calculated by taking the average of entries in each row of A_{norm}:

$$w_j = \frac{\sum_{l=1}^{m} \overline{a}_{jl}}{m}$$

The weight of w_j indicates the importance of the factor j in compare with the other parent factors of the corresponding child node in the model. Weight of all parents of one node should sum up to one.

The process of weighting the parent nodes and developing the conditional probability tables starts from the root nodes as explained in section 4.8.2. Once the weights for each parent node is identified the next step is to calculate the conditional probability table for each node in the model.

7.2: Determining the conditional probabilities

The conditional probabilities for each node can be assigned through inference from historical data if available, but in many cases, the available data are irrelevant or are very limited. Therefore relying on data does not give always an accurate and comprehensive result. The alternative option is to use expert judgment in order to develop the conditional probability tables. Assigning every single probability in the conditional probability table for a big model including large number of nodes (parents and child node) is hardly manageable by group of experts. Another alternative approach is to take a fully 'mechanistic' approach to determine the conditional probabilities. The critic to fully 'mechanistic' approach is that it does not take valuable knowledge from expects or available data into consideration (Røed, et al. 2009). Consequently, the combination of expert judgment and 'mechanistic' approach by use of result from data analysis is the best solution.

A semi ‘mechanistic’ methodology used by (Røed, et al. 2009) in offshore risk analysis. This procedure uses both the expert judgment and a parameterized equation in order to assign the conditional probabilities.

Conditional probability of each state of any of the nodes given the different state of its parents in the conditional probability table can be calculated as following (Røed, et al. 2009):

$$P_j = P_{basis} \sum_{i=1}^{n} w_i \sum_{k=A}^{F} P_{ik} Q_{ik} \quad , \quad P_i \in [0,1]$$

Where:

$\boldsymbol{P_j}$: Represents the corresponding state of considered event in the conditional probability table.

$\boldsymbol{P_{basis}}$: Represents the initial probability of the corresponding state estimated either by experts or by use of statistical data (In this report all the basis probabilities are determined from literatures and presented in chapter 3).

$\boldsymbol{w_i}$: Represents the weight of each parent $\boldsymbol{i} \in [1, \mathrm{n}]$ of the child node. (AHP method for determining the weights of parent nodes explained earlier in this chapter).

$\boldsymbol{P_{ik}}$: Represents the probability of parent node $\boldsymbol{i}$ being in the state of $\boldsymbol{k} \in [A, B, C, D, E, F]$. The presented six states which characterize the state of RIFs adapter from TTS evaluation system (Thomassen and Sørum 2002) which developed later in Barrier and Operational Risk Analysis(BORA) project (Seljelid, et al. 2007) and used in offshore risk analysis by (Røed, et al. 2009).

$\boldsymbol{Q_{ik}}$: Represents the adjustment factor for the parent node $\boldsymbol{i}$ being in the state of $\boldsymbol{k} \in [A, B, C, D, E, F]$. For binary parent nodes which have just two state (best and worst possible), A and F correspond to the best and worst outcome respectively. Table 6.2 presents the suggested adjustment factors for different states of RIFs in the BBN model.

Table 6.2: Adjustment factors for the States that RIFs can be in (Røed, et al. 2009)

State	State characteristics	Adjustment factor Q_{ik}
A	Correspond to the best desired state (the best practice in the industry)	0.1
B	Correspond to a level better than average desired (industry average)	0.55
C	Correspond to average desired state (industry average)	1
D	Correspond to the state slightly worse than average desired	4
E	Correspond to a level considerably worse than average desired state	7
F	Correspond to the worst possible scenario	10

Once the conditional probabilities are assigned to the all states of the nodes, the probability of final event which is uncontrolled fire is calculated.

7.3: Finding the most influencing factors in the model

The main purpose of building a probabilistic network in not just to calculate the probability/frequency of the final event, but also to evaluate the influence of the factors in the model on the outcome scenario. Sensitivity analysis is recommended for evaluating the degree of influence of different factors in the model.

Sensitivity analysis shows how sensitive is any of the propagated evidences from the variation in the value of their parents (which are the entries to the conditional probabilities). This analysis is performed for the outcome node and any other nodes of interest (Kjaerulff 2008). In GeNIe, which used for modeling of BBN in this study sensitivity analysis is performed by selecting the target node of interest and using the ‘tornado function’ in the software interface. The result of sensitivity analysis is a bar chart in which lists the all the factors that contribute to the change in the outcome scenario with their degree of importance. Identification of the most critical factors in the model can help decision makers to adapt the best and most effective risk reducing measures in order to reduce the probability/frequency of outcome event to the desired level.

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