NATIONAL AND TECHNICAL UNIVERSITY OF ATHENS

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DIPLOMA THESIS

Reliability Analysis for Tanker Vessels

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Abbreviations

DAG	Directed Acyclic Graph
OREDA	Offshore Reliability Data Project
ISO	International Standards Organization
SRIC	Ship Reliability Investigation Committee
Loa	Length Overall
LBP	Length Between Perpendiculars
B	Breadth
GT	Gross Tonnage
NT	Net Tonnage
ITC 69	International Tonnage Convention 1969
DWT	Deadweight
SMS	Scheduled Maintenance System
VIT	Variable Injection Timing
PDF	Probability Density Function
CDF	Cumulative Distribution Function
VDR	Voyage Data Recorder
ECDIS	Electronic Chart Display and Information System
MF/HF	Medium Frequency/ High Frequency
GMDSS	Global Maritime Distress and Safety System
ICCP	Impressed Current Cathodic Protection
IQR	Interquartile Range
US	United States
DEREL	Diesel Engine Reliability Database
RAM	Reliability, Availability, Maintainability
INCASS	Inspection Capabilities for Enhanced Ship Safety

Περίληψη

Σκοπός της παρούσας διπλωματικής είναι η ανάλυση αξιοπιστίας των στοιχειών που παρουσιάζουν τις περισσότερες βλάβες στην διάρκεια ζωής ενός πλοίου, βασιζόμενη για τον εντοπισμό τους στην στατιστική ανάλυση αληθινών δεδομένων από βλάβες δεξαμενοπλοίων που συνελέγησαν από ελληνική ναυτιλιακή εταιρεία.

Τα προς ανάλυση δεδομένα αφορούν πάσης φύσεως βλάβες οι οποίες αναφέρθηκαν από τα πλοία προς την εταιρεία για το χρονικό διάστημα δύο χρόνων. Είναι σημαντικό να τονιστεί οτι πολιτική της εταιρείας είναι οτι όλες οι βλάβες πρέπει να αναφέρονται σε ειδική φόρμα, από τις οποίες αντλήθηκαν τα απαραίτητα στοιχεία.

Στο 1^ο κεφάλαιο, μέσω της βιβλιογραφικής επισκόπησης, παρουσιάζεται η έννοια της ανάλυσης αξιπιοστίας και η σταδιακή της ανάπτυξη στον τομέα της ναυτιλίας. Επιπλέον γίνονται αναφορές για τις εφαρμογές της στον μηχανολογικό εξοπλισμό του πλοίου και κυρίως στην κύρια και τις βοηθητικές μηχανές.

Στο 2^ο κεφάλαιο, παρουσιάζεται το θεωρητικό υπόβαθρο της ανάλυσης αξιοπιστίας με απώτερο σκοπό την βαθύτερη κατανόηση βασικών εννοιών που αφορούν τις μεθοδολογίες αξιοπιστίας και την ευρύτερη συνεισφορά τους στην ανάπτυξη της σύγχρονης βιομηχανίας. Πιο συγκεκριμένα γίνεται μια σύντομη ιστορική αναδρομή από την γέννηση της έννοιας της αξιοπιστίας μέχρι σήμερα, ενώ επεξηγούνται οι κύριες μέθοδοι καθώς και τρόπος διαχείρισης των δεδομένων.

Στο 3^ο κεφάλαιο, πραγματοποιείται η στατιστική ανάλυση των πραγματικών στοιχείων που αφορούν τις βλάβες στα εξεταζόμενα πλοία με σκοπό τον καθορισμό των μηχανημάτων που παρουσιάζουν μεγάλη συχνότητα εμφάνισης προβλημάτων. Για την ολοκλήρωση της διαδικασίας αυτής τα αρχικά δεδομένα χωρίστηκαν σε κατηγορίες με βάση το πρόγραμμα συντήρησης της εταιρείας και την χωροταξική διάταξη ενός πλοίου, ενώ κάθε κατηγορία διαιρέθηκε σε υποκατηγορίες με κριτήρια αυτή την φορά τον αριθμό των βλαβών, την σημαντικότητα του εξοπλισμού αλλά και το πρόγραμμα συντήρησης της εταιρείας. Αποτέλεσμα της διαδικασίας αυτής είναι η παραδοχή οτι η κύρια μηχανή και οι βοηθητικές μηχανές είναι τα πιο ευάλωτα μηχανήματα σε βλάβες, ενώ η περαιτέρω ανάλυση οδηγεί στο γεγονός οτι το σύστημα πετρελαίου των μηχανών αυτών παρουσιάζει τις περισσότερες βλάβες.

Στο 4^ο κεφάλαιο, παρατίθενται οι θεωρητικοί και μαθηματικοί ορισμοί της μεθοδολογίας που θα ακολουθηθεί για την ανεύρεση της αξιοπιστίας. Αναλύεται η παραμετρική και η μη παραμετρική μέθοδος που θα χρησιμοποιηθεί καθώς γίνεται και εκτενής περιγραφή των εξισώσεων τους.

Στο 5^{o} κεφάλαιο, γίνεται η ανάλυση αξιοπιστίας του συστήματος πετρελαίου της κύριας μηχανής και των βοηθητικων μηχανών. Αρχικά παρουσιάζονται οι ώρες λειτουργίας των εξαρτημάτων μέχρι να παρουσιάσουν την βλάβη, οι οποίες αποκτήθηκαν από την ναυτιλιακή εταιρεία. Στην συνέχεια με την βοήθεια του προγράμματος “Statgraphics Centurion” υπολογίζονται και παράγονται οι στατιστικές κατανομές και οι καμπύλες αξιοπιστίας που περιγράφουν τις εν λόγω βλάβες. Ειδικότερα, εξάγονται και σχολιάζονται διαγράμματα δεσμευμένων πιθανοτήτων βλάβης, επιβίωσης και ρυθμού βλάβης όπως και τα αντίστοιχα αποτελέσματα τους σε πίνακες. Οι ίδιες καμπύλες παρουσιάζονται για παραμετρικές και μη παραμετρικές μεθόδους όπως αναφέρθηκε προηγουμένως.

Στο 6^{o} κεφάλαιο, παρουσιάζονται τα συμπεράσματα της παρούσας διπλωματικής εργασίας, καθώς επίσης και προτάσεις για μελλοντική έρευνα.

Abstract

The purpose of this thesis is the reliability analysis of the equipment with the most failures in the life of a vessel, based on the statistical analysis of real failure data collected by a Greek shipping company, referring to tanker vessels.

The data to be analyzed relate to any kind of damage reported by the ships to the company for a two year period. It is important to mention that the company's policy is that all malfunctions must be reported in a special form, from which the necessary data were obtained.

The 1st chapter, through the literature review, presents the concept of reliability analysis and its gradual development in the shipping sector. Moreover, references are made to the applications of the method in vessel's equipment and mainly to the main and the auxiliary engines.

In the 2nd chapter, the theoretical background of the reliability analysis is presented with a view to a deep understanding of key concepts concerning the methodologies of reliability and their boarder contribution to the development of modern industry. More specifically, there is a brief historical flashback from the birth of the concept of reliability to the present, while the main methods and the management of the data is being explained.

In the 3rd chapter, the statistical analysis of the field data relating to the vessels failures is carried out in order to determine the equipment with the highest index of failures. To complete this process the original data were divided into categories based on the company's maintenance plan and the spatial arrangement of a vessel, while each category was divided into subcategories with criteria this time the number of failures, the importance of the equipment and the maintenance program of the company. The result of this process is the assumption that the main and the auxiliary engines are the most prone to malfunctions. Further analysis on these machineries leads to the fact that the fuel oil system presents the most malfunctions.

In the 4th chapter, the theoretical and mathematical definitions of the methodology to be followed for the reliability analysis are presented. The parametric and non parametric method is analyzed and an extensive description of their equations is displayed.

In the 5th chapter, the reliability analysis of the main and auxiliary engine's fuel oil system is performed. Initially, the operating hours till failure of the components are presented, which were acquired by the shipping company. Then using the program ”Statgraphics Centurion” the statistical measures and the reliability curves are

calculated and produced. In particular cumulative distribution plots, survival plots and hazard rate plots are exported and commented. The same curves are presented for parametric and non parametric methods as mentioned earlier.

In the 6th chapter, the conclusions of this thesis are provided, as well as proposals for future research.

INTRODUCTION

Shipping industry till the ancient times is connected with the global trade and transportation. It can be said with confidence that during the last decades has established its position in the global economy by making possible the safe and easy transportation of necessary materials and goods among the whole world. The numbers can speak itself since the world's commercial fleet for 2018 was constituted by 94,171 vessels with combined tonnage of 1.92 billion deadweight (DEVELOPMENT, 2018).

The important role of the shipping industry in this worldwide economy is easy to assume that comes with great responsibility. From the safety of the cargo till the very strict timetables there are numerous aspects that have to be ensured in order to make the trade reliable and profitable. That means that the fleet must be fully operational and trouble free in order undesirable cases such as crew and passengers accidents, delays, collisions, cargo contamination, environmental pollution etc. to be avoided (C. Guedes Soares, 2001). To achieve that, the most crucial factor that must be taken under consideration is the machinery's trustworthy and reliability.

Through the centuries the wooden vessels operated by oars and afterwards by sails gave their position gradually to big steel structures, self propelled by diesel engines and fully equipped making them autonomous to sail through the seas. Although, the marine technology and equipment have undergone a rapid evolution since today, altering the course of history, it is observed that several systems and machineries on board are frequently malfunctioning and most of the times out of the maintenance schedule. This fact is clearly showing to the science and engineering community the necessity that exists for further research and improvement (Raymond F. Zammuto, 1992).

The great amount of information which already exists through all these years that the industry is operating and evolving is the key factor for improvement (Kececioglu, 2002). The study of the economical, operating, failure and maintenance data combined with methods of reliability and availability analysis can give tremendous results in development of more reliable, safer and costless equipment. More specifically, different models capable to determine the cost benefits can be produced by comparing the maintainability and time till failure of similar equipment, prediction of malfunctions can be achieved giving the advance to the shipping companies to develop strategies regarding their spare parts inventory, choosing manufacturer, evaluating and prioritizing their maintenance schedule.

1 LITERATURE REVIEW

The concept of assessing the probability of future events is dating back at least to the 17th century. Throughout the years and as the industry evolving different branches were embraced this concept, all of them under the same idea to establish “infrastructure of confidence” (Fragola, 1996). The necessity of acquiring the best prediction of confidence and trustworthiness gave birth to reliability analysis, the catalyst for this method to grow resonance was the often failures of the vacuum tube in World War II which prompted the US department of defense to initiate a series of studies. From that point forth the idea of reliability met great development and gradually was assimilated in the section of engineering as a technical discipline (J.H. Saleh, 2005). From the engineering point of view the initial idea remained the same and applied to many technical application aspects, however the main attribute is concentred to the prediction that an item will perform the intended functions under specified conditions for a specific time. To evaluate these probabilities of reliability many methods have been introduced in the last decades and they are keep evolving with purpose to study and produce the best approximated probabilistic models from the data that acquire (M. Azarkhail, 2011). Together with the rising of the computational power different software were developed, in order to analyze the plethora of raw data and create different types of life models. As Meeker and Escobar mention using the SAS software a wide spectrum of data like time to failure, censored, uncensored, from repairable systems or accelerated life were analyzed for reliability purposes (William Q. Meeker, 1997). This combination of statistics, programming and failure data raised the standards and led the way for safer and more reliable systems and products, drawing the attention of the marine industry.

The global competition, the higher customer expectations and the strict regulations forced the marine industry to invest in studying of reliability methods in order to increase their productivity, improve the maintainability of their systems and set a safer environment. The US cost guard, pioneer on this field, created a prototype database for the collection of failures for the diesel engines and the assessment of their reliability with the name DEREL (N.A. Moore, 1998) aiming for the development of a better reliability concept. A variety of similar failure data gathering and reliability evaluation programs have been conducted mainly by the collaboration of corporations and administrations around the world in the effort to maximize the reliability, availability and maintainability characteristics of ship’s machinery, example of this movement is the RAM database (Inozu, 1996). One of the most recognized initiated by the committee for ship reliability investigation in Japan producing numbers of failure rate for the machinery of a vessel (Kiriya, 2001). Another example that establishes the significance of reliability analysis is that the American Bureau of

Shipping one of the biggest classification organization in the world made the appropriate moves in order to design its own reliability based platform in the foundation of creating risk based models and adjusting the regulations in the future (Jorge Ballesio, 2002).

Despite the fact that there is a wide spectrum of related to risk sources like the human error or external events, the majority of the researches was concentrated around the axis of equipment failure, either individually either as a system. The engineers using probabilistic methods managed to create qualitative and quantitative risk based models for the vessel's equipment (Bilal M. Ayyub, 2002) allowing them to develop safer products, to manage their maintenance and spare parts planning, improve the cost effectiveness and overall to make decisions with the risk as a known factor. On this aspect Baliwangi utilized the Monte Carlo method to develop a reliability prediction model for a ship's propulsion system (Baliwangi, 1999). Considering that the marine propulsion system is the heart of the ship similar analyses have been carried out, following the strategy of dividing the system to subsystems and examine the interaction with each other and the influence that appear to have into failures of the system (Conglin Dong, 2013). Different approaches, centered on this matter, focus on different subsystems and aspects that affect the vessel's seaworthiness. Results have been shown that the age of the vessel is one of the elements leading to more failures (Okazaki, 2016), also is making clear that the confluence of individual elements in a system can change positive or negative its reliability (Tran Van Ta, 2016). However one common that all these researches have is that the failure rate of the main and the auxiliary engines of a vessel is high, something that is depicted in Prichett's thesis in his effort to design an improved reliability centered maintenance method (Pritchett, 2018).

The demand for global and punctual on time trade is bigger than ever, a possible collapse of the main engine or the auxiliary engines, which are responsible for the propulsion of the ship and the generation of power respectively, is undesirable. Loss of the engines is translated to enormous costs, possible loss of hire and set the human life in danger since they are the most responsible machineries for the increasing of failure rate and decreasing of reliability for the vessel as whole, the probability of possible malfunctions grow along the operating time contributing to the risk of total failure (Karadimas, 2010). Establishing the influence of these machineries to high risk of potential hazards the scientific community proceeded to their deconstruction to smaller subsystems in order to appreciate the root causes of the problem. These procedures pointed out that the subsystems of the machineries are the most contributing to the increasing of the unavailability of the system. Especially for the main engine the air supply system and the fuel oil system are the most sensitive and prone to malfunctions (Akkaya, 2013). A study in University of Strathclyde using as a tool the INCASS machinery reliability assessment to evaluate main engine's components reliability indicated that the fuel injection and the air inlet system have higher probabilities of failure than the other components, even in the case that the main engine is in good working condition (I. L. Konstantinos Dikis, Atabak Taheri, Gerasimos Thetokatos, 2015). Dikis and Lazakis taking under consideration the above study and motivated to involve a holistic consideration of operational and failure interdependencies among multiple components within the same or different systems, performed an analysis regarding the air supply system by collecting and examining raw data of main engine failures regarding the system. They classified the most important components that contribute the air supply system and calculated the probabilistic machinery reliability depending on time, the result showed that the injectors and piston rings obtain the weakest reliability performance (I. L. Konstantinos Dikis, 2019). A similar case study according the scavenge air system displayed that another component which contributes to often failures is the turbocharger (M. Anantharaman, 2018). The two researchers using the same technique evaluate the working state reliability performance of the fuel pumps of the main engine and compare the results with the manufacturer's limit (Iraklis Lazakis, 2016).

Establishing the failure behaviors and the potential risks that define the components of a vessel is a major accomplishment of the engineering community. In that way safer and more reliable products and systems can be produced, knowing the root cause of the problem experimental studies conducted using in-cylinder pressure and acoustic emission techniques in order to identify and comprehend the structure of the fuel injection malfunctions (Tian Ran Lin, 2011). Also working on tests to reliable simulation models the malfunctions can be simulated and their results to the system can be evaluated (Giovanni Benvenuto, 2007). In addition preferable maintenance strategies can evolve achieving the maximum capability of the equipment with the lowest cost with the use of failure modes and effect analysis (I. Lazakis, 2009).

2 RELIABILITY ANALYSIS

The last five decades the idea of reliability analysis is growing rapidly in the engineering establishing a scientific discipline with cornerstone the theory of statistics and probability which originated by Blaise Pascal and Pierre de Fermat (Figure 1). The concept of reliability prediction arises in 1900 when mass production makes its appearance with leader Henry Ford and his Model T car. However the concept of reliability was emerged in the World War II, the catalyst for this to happen was the vacuum tube, more especially the triode invented by Lee de Forest in 1906. The failure of the vacuum tubes prompted the US department to initiate thorough studies and researches which eventually led to the establishment of the reliability engineering (J.H. Saleh, 2005).

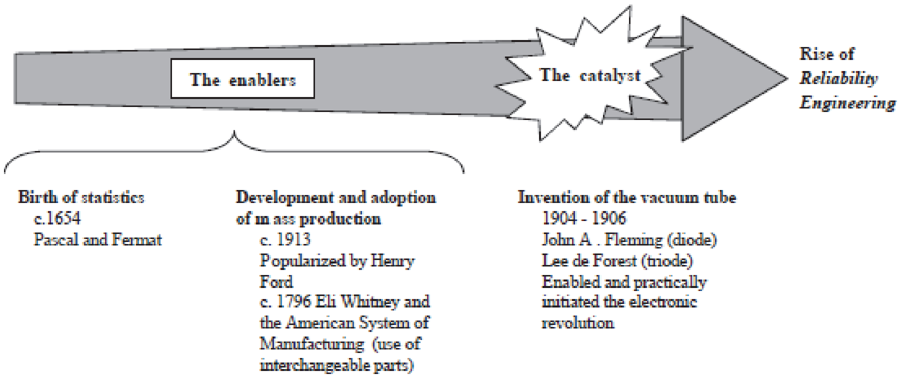

Figure 1: Enablers and the catalyst of reliability engineering: statistics, mass production, and the vacuum tube.

In the following decades reliability engineering continuous to expand more and more with steady steps. The exponential distribution developed in the 1950s gave its place in the 1960s to other reliability models such as the Weibull and the lognormal distribution, the main reason was that till that time the previous models did not take under consideration the aging of the system and the ability to be repaired leading to unrealistic results. In 1970s the necessity of safety assessment mostly in the aerospace, gas oil, chemical and nuclear power industry initiated a new approach of the subject giving birth to fault tree analysis, systems analyzed in reliability block diagrams and fault tree/event tree applications estimating the levels of risk, reliability and safety. The rapid development in the mass production in combination with the decreased budgets for research had as a result the in 1980s to give emphasis to greater results with the minimum information. Root cause analysis to failures developed the accelerated life model a flexible model requiring minimum failure data although till then was not so trustworthy since many assumptions had to be made. Another chapter of the 1980's was the Bayesian model which used to update the probability of a hypothesis using experts opinions and previous experience, however the complexity of the calculations and the need of programming made this model hard to use. In the next two decades the breakthrough in computer technology lays the foundation for the reliability engineering, the ability to predict accurately the expected lifetime of a component or potential failures of a system using failure data from the past has a huge impact in the cost effectiveness, safety and reliability of the industrial business. In early 1990s the US Army launches two reliability physics programs, in 2000s the maximum likelihood estimation method is being introduced by Fischer and the Bayesian analysis taking advantage of the computational advancements finds fertile ground to grow. Many years of evolution have managed to make reliability analysis a great tool nowadays possible to evaluate the technological mistakes of the past and capable to secure new ideas with cost, safety and failure predictions (M. Azarkhail, 2011).

2.1 Reliability Analysis Methods

Since reliability depends on many factors making the procedure of determining it very complex a lot of methods were developed in order to achieve the most effective approach of the subject.

Some of them are presented below.

2.1.1 Maximum Likelihood Estimation

Maximum likelihood method is general applied for calculating parameter estimators for life time models formed by a large sample size. It offers consistent and reliable estimators which are a minimum variance estimator and a minimum mean square error. Even for small sample groups the estimation can be trustworthy. The hypothesis behind this technique is that the calculated parameters of the observed data maximize the likelihood that the selected population is the most probable for the produced model which describes the process.

For the better understanding of the method a sample size n with independent variables x_1, x_2, … x_n can be assumed taken from a population which its probability density function is f(x;θ).

The probability function can be written in order to describe this specified sample of the population:

$$L(\theta) = f\ (x_1, x_2, \dots x_n\ ; \theta) = \prod_{i=1}^{n} f(x_i\ ; \theta)$$

The likelihood function is not still describing the probability of the sample but shows a quantification equivalent to that probability. There are many ways in real life scenarios that the derivative of the function can be estimated in order to find the maximum point which describes the maximum likelihood estimator of the unknown population (Schuller, 1997).

2.1.2 Markov Chain Monte Carlo

Markov chain Monte Carlo is a technique based on simulation able to estimate the posterior distribution of a given parameter in a complex probabilistic space. The Markov method is one of the most advanced and is considered a great tool in the reliability and risk analysis.

The probabilities in Markov chain have a stationary transition and each one is time dependent from the other making that way a memory less system. That means that each event is separate from the history events.

In order to evaluate the expectation of a function $g(\theta)$ over a probability density function $f(\theta)$, $f(\theta)$: $E_f[g(\theta)] = \int g(\theta) f(\theta)\, d\theta$ if we take samples using the Markov chain generating iterate value $\theta(i)$ only by taking under consideration the previous value $\theta(i-1)$, this technique is known as the Markov Chain Monte Carlo (Gilks, 2005).

2.1.3 Bayesian Network Method

Bayesian network are commonly used to for making future predictions and explaining observations. These networks are a type of probabilistic graphical model combining different conditional probabilities or density probability functions and resulting the final effect which have upon the under examination system and how they react with each other. This system is called directed acyclic graph (DAG) and consists of random variables presented as nodes. Depending the probabilistic problem, appropriate relationships are created between these nodes providing a compact representation of a joint probability.

This method can be categorized in two types regarding the used data set, especially when the data set is small, the non constraints based method and the constraints based method. Their main difference is that in the first one there are no constraints between the parameters. When the data are insufficient the constraints based method is preferred (Xiao-guang Gao, 2019).

To simplify the Bayesian approach the main idea can be divided in three tasks which must be explained and these are the reason, the model and the evidence (Changhe

Yuan, 2011). The reason refers to the process and the theoretical background which followed in order to conclude to certain results establishing that way the credibility of them. The analyzing of the method is the next step and its goal is to explain the initial knowledge in Bayesian network coding. Last but not least is the explanation of the evidence in which the reasoning of the chosen parameters and their relationship with each other must be established.

2.2 Establishment of Failure Data

Inseparable piece of a statistical/reliability analysis is a set of data specified in the study. Most of the times these data concern failures of a system and they called failure data.

There are practically two ways to gather failure data, the first one is to carry out a specific test as an experiment for multiple times maintaining the other parameters that affect the system stable, the data produced by this process are known as experimental data. In many cases the experimental data have a high cost to be produced and their amount is limited. The second group of data is collected from practice meaning that are data of a system under actual operating conditions. Field data as is their name are often hard to find and their recording must be thoroughly examined and established because a wrong set of data may be misleading (Schuller, 1997).

It is needless to mention that an accurate and well recorded set of data is half of everything, the acquisition, categorization and clarification of these data is the key factor to reliability techniques.

2.3 Reliability Data Collection Projects

The essence for new approaches to the plan maintenance system, to improved designs and increased productivity led the industry to create reliability data banks id est projects composed by marine companies gathering information of failure data from real life operation through the years.

2.3.1 Offshore Reliability Data Project (OREDA)

Offshore reliability data project in short OREDA is a data collection program running for more than thirty five years (H. Langseth, 1998). Specifically it was initiated in 1981 from Norwegian Petroleum Directorate with primary objective to gather information for the safety equipment and was formally begun as oil company joint industry project in 1983. The project is supported by 7-11 oil and gas companies and its main scope is the collection and exchange reliability data. The database holds 39000 failure 73000 maintenance records from 17000 equipment units of 278 installations. As evident of its significance is the International Standards Organization ISO 14224: *Petroleum, petrochemical and natural gas industries -- Collection and exchange of reliability and maintenance data for equipment* which based on the OREDA concept and the analysis results (OREDA, 2018).

2.3.2 Committee for Ship Reliability Investigation (SRIC)

SRIC database system which have never been out of Japan was conducted in 1982 by industrial, academic and administrative sectors and its full name is the Committee for Ship Reliability Investigation. At first the case study was the ship MO of a Japanese shipping company. Despite its huge success and the involvement of a large group of Japanese companies the program was terminated after ten years, but after of the continuous pressure for its re activation and the support of the Ministry of Transport the project was started again as National Maritime Research Institute. The database includes over than 11,400 field data for multiple types of failures and equipment (Baliwangi, 1999).

2.4 Data Censoring

In lifetime data analysis censoring of the data is very common. Since the researches are practically performed in limited timelines becomes understandable that all the failures cannot be occurred and this is the reason for censoring (Freeman, 2010).

There are three types of censored data:

- Right censored: The known values are exceeding a curtain value, for example a pre fixed lifetime. There are two types of right censored data the Type I and Type II.
    - Type I censored: The values that exceed a pre arranged value and survive are Type I censored, for example a random outcome of values x of a population N which exceeds an experiment of curtain time t.
    - Type II censored: Type II is failure censoring and is used in designed experiments, for example this time the population N and the values of the expected outcome x are fixed but the time that the x will occur is unknown.
- Left censored: The known values are less than a curtain value, for example a failure which occurred before a particular time.
- Interval censored: The known values are in between two interval values, in this situation the exact time of a failure cannot be known.

Other groups of data sets are the truncated and the uncensored data.

- Truncated: The values are recorded or not depending on if some predefined limits are exceeded.
- Uncensored: The values are recorded as given.

In general censoring occurs when incomplete information is available about the survival time of some individuals. Below are presented some examples of censoring.

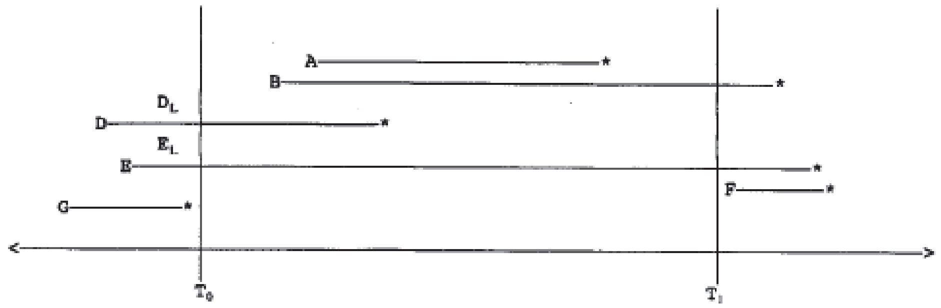

Figure 2: Examples of data censoring

In Figure 2 are presented several censoring examples, the continuous line represents the life period of each subject while the asterisk indicates the occurrence of an event of interest. The lines T0, T1 are the specified time limits of observation time. This defined timeline of observations where the time of censoring is known, called point censoring and resulting when the data are closely monitoring or the time of occurrences are well logged. The case A in Figure is inside the time limits as well as the time of occurrence of the event of interest, this observation needs no censoring and can be considered as uncensored. The case B is an example of right censored data, since the observation period exceeds the limit T1 event of interest occurs after this point. Case D represents truncated data, which are not commonly arising in engineering. In some rare cases the data may be both right and left censored, this is presented in case C and is called doubly censored. If the staring period (E_L) of this observations is documented then these data can be described as uncensored or right censored, however if this initial time is unknown then the data may affect the results and is preferable to exclude them form the analysis. In case G and F the observations experience the event of interest before the start or after the end of the observation time, these data are called completely left censored and completely right censored respectively.

Another type of data censoring which can often be found in engineering is the interval censoring. In this case (Figure 3) instead of knowing the time that the event of interest occurred, the known time is the one between the interval S_L, S_R. An example of this case is if one examines the failures of equipment and instead of its operating time till failure the only known value is that the failure happened in time S_R after a maintenance time S_L.

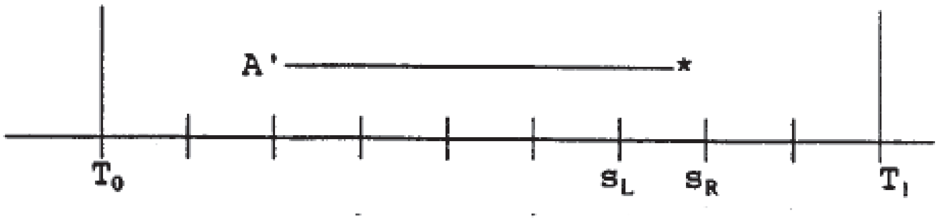

Figure 3: Example of interval censoring

There are many approaches of dealing with censored data like the complete data analysis where the censored data are excluded from the analysis, however this method lacks to efficiency and leads to estimation bias. The imputation approach is one popular method which one certain assumption is being followed in order to deal with the censored data. The most effective approach though, is the likelihood based, because uses methods of estimation that are adjusted to censored and uncensored data.

With some exceptions, the censoring mechanisms in most observational studies are unknown, the researchers must estimate the censoring type that they deal with before the beginning of any study since wrong assumption for the censoring mechanism may lead to misleading results (Kwan-Moon Leung, 1997). In the present thesis the data are used as given so they are uncensored data.

3 STATISTICAL ANALYSIS

This chapter obtains the statistical analysis of the collected failure data. Purpose of this analysis is to identify the equipment which presented to be the most prone to malfunctions in order to be analyzed deeper in the following research.

3.1 Collection and Analysis of Failure Data

The gathered information were obtained by a Greek shipping company which manages a fleet of thirty five vessels both tankers and bulk carriers servicing international trade of perishable products and general cargo.

The under examination data regard to component failures of thirteen tanker ships during the time period of two years. These time to failure field data acquired from the planned maintenance system of the company in combination with the relevant forms and the correspondence with the vessel when it was needed, and they are in total 1,479.

Table 1: Fleet main characteristics

A/A	VESSEL'S NAME	DATE OF BUILD	FLAG	Loa (m)	LBP (m)	B (m)	D (m)	DRAUGHT	GT (ITC 69)	NT (ITC 69)	DWT
1	Vessel No.1	27/4/2004	Isle of Man	228	219	32.27	20.4	12.22	42.172	19.551	70.681
2	Vessel No.2	28/5/2004	Isle of Man	228	219	32.27	20.4	12.22	42.172	19.551	70.616
3	Vessel No.3	28/7/2005	Isle of Man	228	219	32.27	20.4	12.22	42.172	19.551	70.675
4	Vessel No.4	9/9/2005	Isle of Man	228	219	32.27	20.4	12.22	42.172	19.551	70.753
5	Vessel No.5	12/10/2005	Isle of Man	228	219	32.27	20.4	12.22	42.172	19.551	70.558
6	Vessel No.6	16/6/2004	Isle of Man	183	173	32.2	19.1	13.22	30.095	13.701	51.314
7	Vessel No.7	30/6/2008	Isle of Man	228	219	32.2	20.9	14.41	42.416	22.071	74.995
8	Vessel No.8	19/8/2008	Isle of Man	228	219	32.2	20.9	14.41	42.296	22.071	74.998
9	Vessel No.9	10/11/2008	Isle of Man	183	174	32.2	18.8	12.22	29.605	11.921	46.609
10	Vessel No.10	3/9/2008	Isle of Man	183	174	32.2	18.8	12.22	29.605	11.921	46.583
11	Vessel No.11	18/7/2008	Isle of Man	183	174	32.2	18.8	12.22	29.605	11.921	46.606
12	Vessel No.12	17/11/2008	Isle of Man	183	174	32.2	18.8	12.22	29.605	11.921	46.609
13	Vessel No.13	10/7/2003	Isle of Man	228	219	32.2	20.4	13,7	41.397	18.792	70.201

In table 1 are presented the main characteristics of the vessels. More specifically their date of built, their registered flag, their net tonnage (NT) and gross tonnage (GT). Also one can see their major dimensions which are the length overall (Loa), the length between perpendiculars (LBP), the breadth (B), the Draught and their weight carrying capacity the deadweight (DWT).

In addition the vessel 1~5, 7~8 and 9~12 are sister vessels and in the analysis are named as Vessel Group No.1, Vessel Group No.2 and Vessel Group No.3 respectively.

In order to quantify the failures of the fleet, they were divided in 9 categories based on the spatial planning of a vessel and the company's scheduled maintenance system (SMS): Engine Room, Deck, Bridge, Ballast Tanks, Cargo Tanks, Accommodation and Hull.

On this basis the following graph can be obtained.

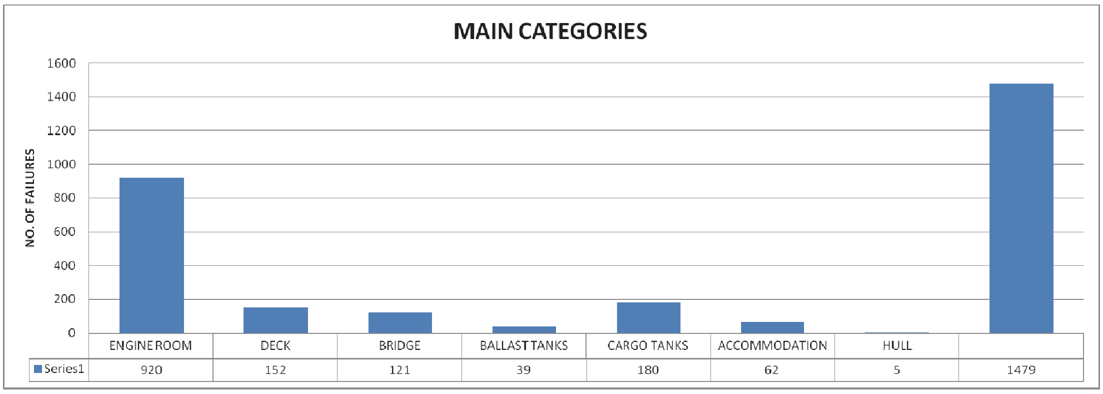

Figure 4: Number of failures regarding each category for the entire fleet

From the Figure 4 is concluded that the most failures take place in the engine room, since 920 out of the 1479 defects concerning the Engine Room or in other words 62%.

Following the categories of the Cargo Tanks, the Deck and the Bridge with significant less defects. The Accommodation, Ballast Tanks and Hull are the categories with the fewest failures.

The above observations can be seen even better in Figure 5 where the failure data of each category are divided by the number of the ships multiplied with the number of the years that are examined, in that way is calculated the failures per ship year.

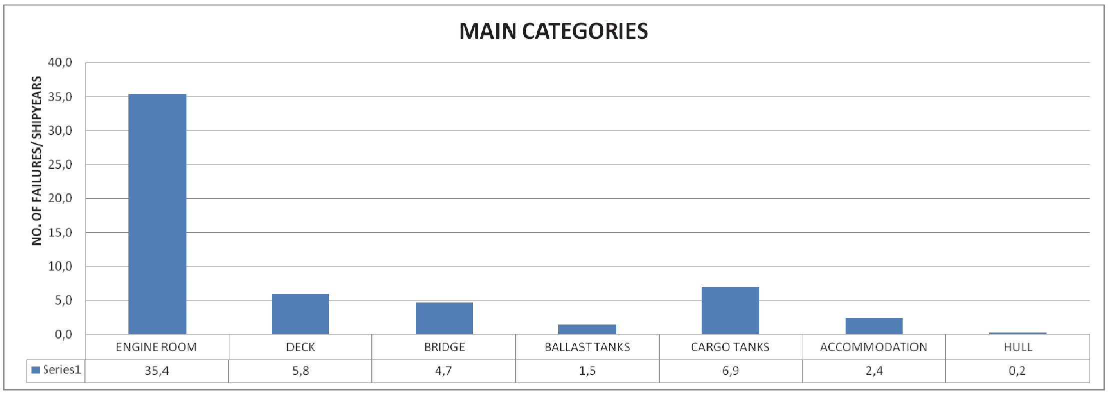

Figure 5: Number of failures divided by the ship years regarding each category

As a conclusion (Figure 5) a vessel is expected to have approximately 36 failures regarding the Engine Room machinery and around 7 failures regarding the Cargo Tanks which is the second largest category. The large difference between the Engine Room category and the others is an expected outcome if one considers the fact that the heavy machinery of a vessel (e.g. main engine, boiler, auxiliary engines, etc.) is located in the engine room.

Considering the differences between the main characteristics of the vessels is considered necessary to observe the variances between the total failures of each one and in each category separately.

Table 2: Number of failures for each vessel and category

A/A	VESSEL'S NAME	TOTAL FAILURES	ENGINE ROOM	DECK	BRIDGE	BALLAST TANKS	CARGO TANKS	HULL	ACCOMMODATION
1	Vessel No.1	154	117	11	7	5	10	0	4
2	Vessel No.2	79	45	8	7	1	13	1	4
3	Vessel No.3	104	64	13	13	1	9	0	4
4	Vessel No.4	91	63	10	6	1	10	0	1
5	Vessel No.5	129	64	17	8	11	24	0	5
6	Vessel No.6	101	57	9	4	5	19	2	5
7	Vessel No.7	149	101	8	12	3	16	0	9
8	Vessel No.8	119	75	10	16	0	12	1	6
9	Vessel No.9	86	50	8	9	1	12	0	6
10	Vessel No.10	141	91	11	14		15	0	10
11	Vessel No.11	114	68	17	6	4	14	1	4
12	Vessel No.12	106	70	11	5	2	12	0	5
13	Vessel No.13	111	28	20	17	2	13	0	2

The Table 2 summarizes the defects for each vessel in total as well as for each category. These numbers can be visualized in the next figure.

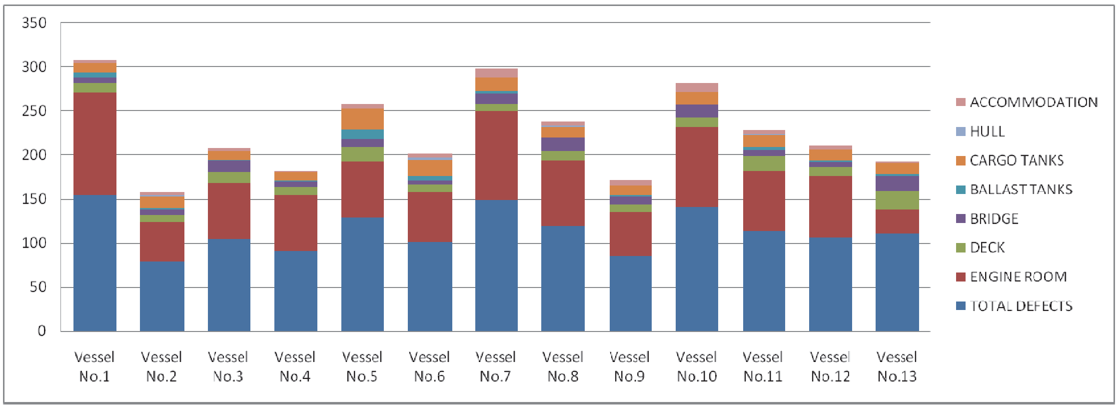

Figure 6: Number of failures for each vessel and category

Despite the fact that the failures are not evenly shared among the vessels, the pattern which observed earlier is being established. It is now clear that for every vessel the most failures concern the Engine Room and the next largest categories are the Cargo Tanks, the Deck and the Bridge followed by the Ballast Tanks, the Accommodation and the Hull.

3.2 Analysis of Failure Data for Sister Vessels

A better approach to identify if the above conclusion is safe, is to examine the group of sister vessels and observe if the failures are distributed in the same categories among them. The advantage of the sister vessels is that they have the same structure, machinery, dimensions and date of build eliminating in that way most of the factors that contribute to failures and giving a better picture of their appearance.

The two largest groups of sister vessels are the Vessel Group No.1 and the Vessel Group No.3 consisted by 5 and 4 vessels respectively and their failures are analyzed below. Part of the analysis including more figures can be found in the APPENDIX A.

3.2.1 Vessel Group No.1

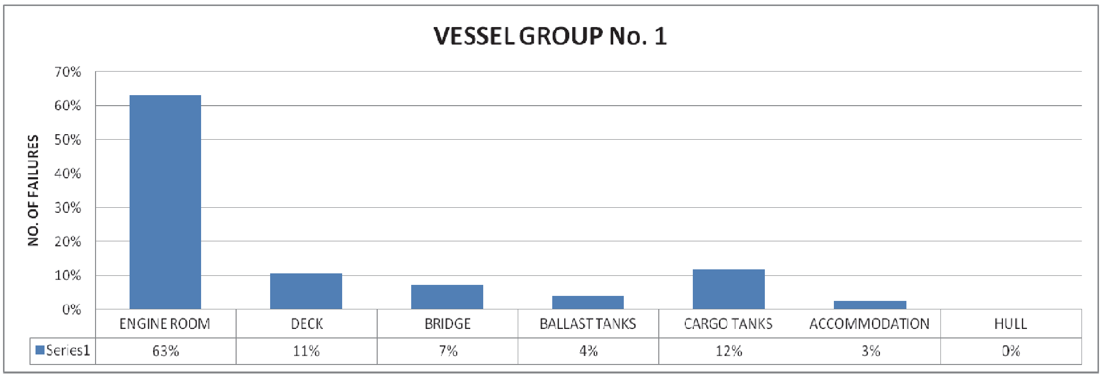

Figure 7: Percentage of failures for vessel group No.1 regarding each category

Figure 7 illustrates the percentage of the failures appearance for the Vessel Group No.1. Over the half of the defects (63%) appear to the equipment of the Engine Room, meaning that these malfunctions are more than the malfunctions of all the other categories combined.

However in order to establish that this chart depicts the real picture of the failures distribution among the sister vessels of the Group No.1 the following figure (Figure 6) contains the defects of each vessel. The number of the defects regarding this illustration can be seen in Table 2.

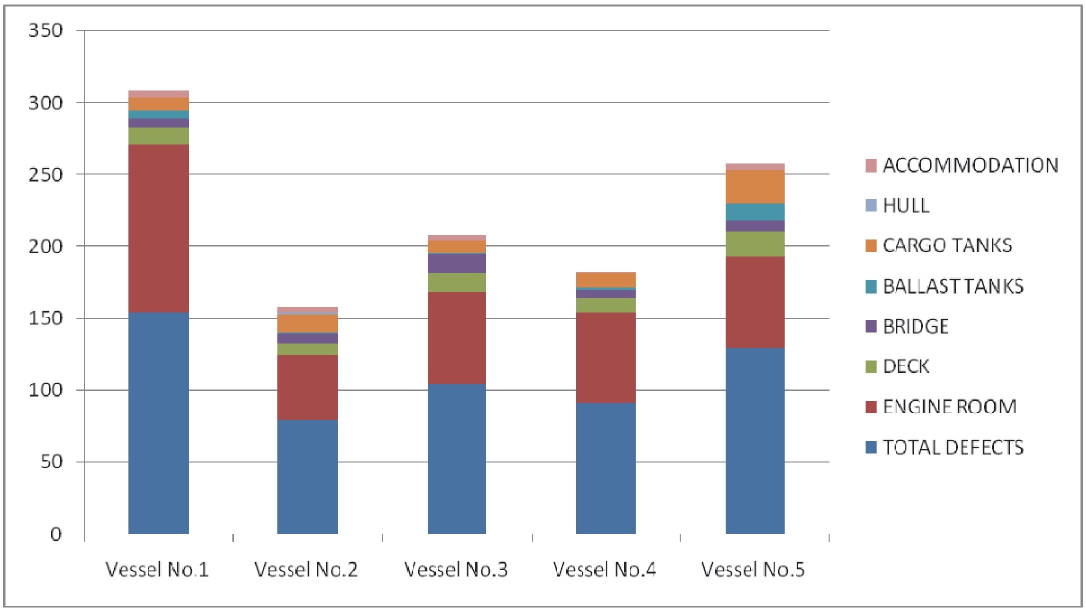

Figure 8: Number of failures for each vessel of sister vessels group No.1 regarding each category

Even though there is a divergent between the numbers of the failures for each vessel the size of each category presents a stability (Figure 8). More specifically all five vessels appear to have most of their failures in the Engine room machinery and the three largest categories that follow are the Cargo Tanks, the Deck and the Bridge. The defects in the Hull, Accommodation and the Ballast Tanks are very small in compare with the others except of the last one for the Vessel No.5 which seem to be significant, however is a single incident and does not affect the conclusion of this analysis.

3.2.2 Vessel Group No.3

The same figures were produced regarding the Vessel Group No.3. The Figure 9 presents the percentage of the failures appearance for the Vessel Group No.3, as one can find out that the results are very similar with Figure No. 5 and the same observations can be extracted.

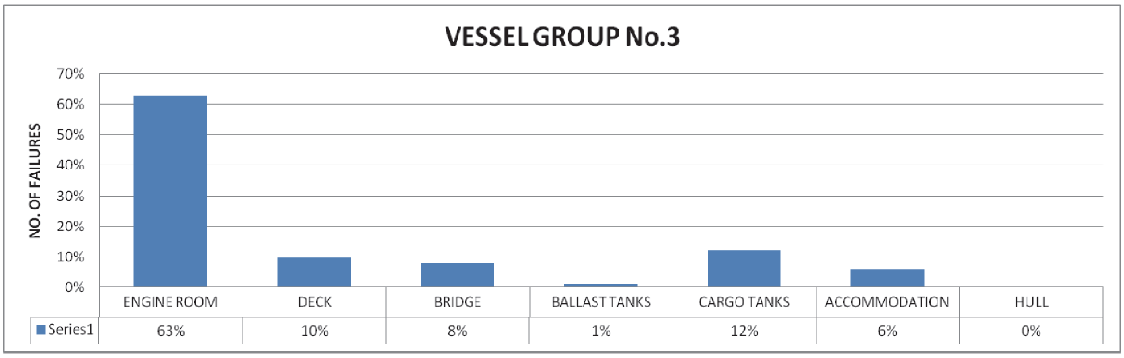

Figure 9: Percentage of failures for sister vessel group No.3 regarding each category

In addition the Figure 10 shows that the categories of failures are shared proportionally evenly for each one of the four vessels of the group. For example the Vessel No.10 has more defects than the other vessels nevertheless the each category is expanding relatively in relationship with the other vessels. The data of Figure 8 are included in Table 2.

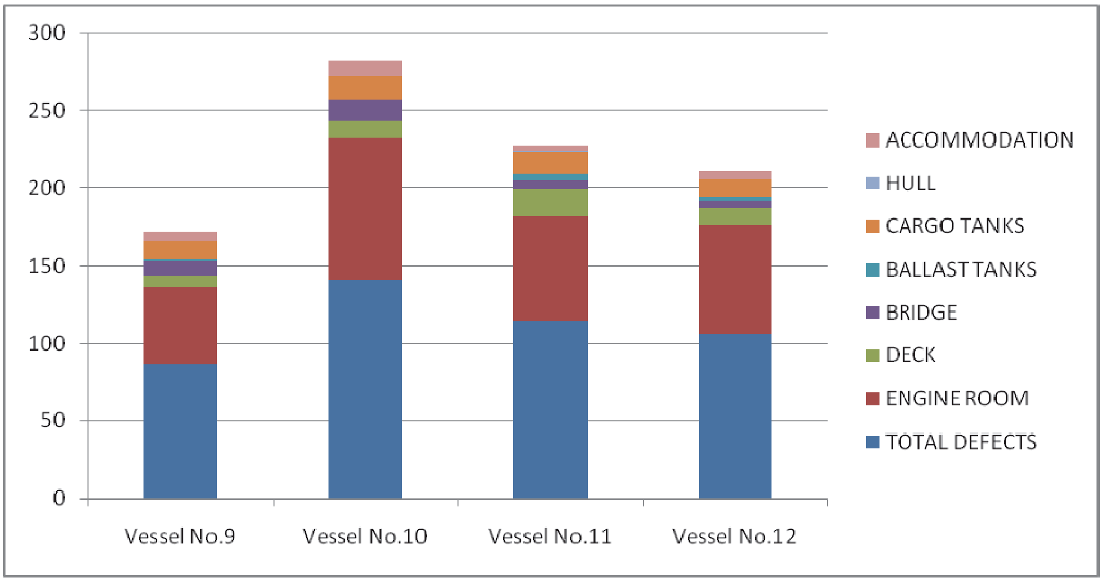

Figure 10: Number of failures for each vessel of sister vessels group No.3 regarding each category

The sister vessels as it was expected seem to have a very similar distribution of the defects that occur on board. Small differences are normal to exist since more than one factor is responsible for machinery's failure except of its expected life time, like the operational conditions or the human factor (Conachey, 2005).

As a conclusion of this analysis can be said that is safe to examine all failures together and not for each ship separately since the data are evenly mete to all vessels. The general outcome is that in the engine room equipment are meet the most failures.

3.3 Subcategories of the failure data

The above analysis can be specified even more since every category is consisted by a variety of machineries, for example in the engine room are located the auxiliary engines, the main engine, the boiler, various pumps and a variety of other equipment serving each one their own purpose.

For that reason following the same approach as before the main categories were divided further to smaller subcategories. In that way the machineries that obtain frequent malfunctions could be identified.

The subcategories were chosen according to the significance of each equipment and the number of malfunctions that occurred. Also under consideration was taken the company's planned maintenance system in the accordance of which these are the major categories of inspection of each category.

In some cases one subcategory is a machinery like the main engine and in other cases is a group of machineries like the pumps, or describing a system composed by more than one machineries such as the mooring arrangement.

The subcategories can be seen in the next figures.

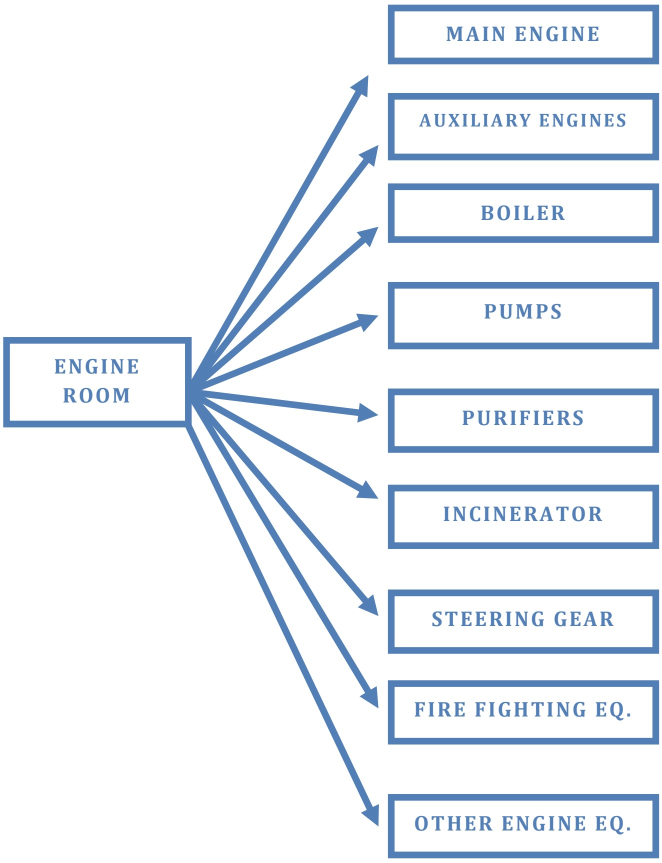

Figure 12a: Subcategories of the Engine Room

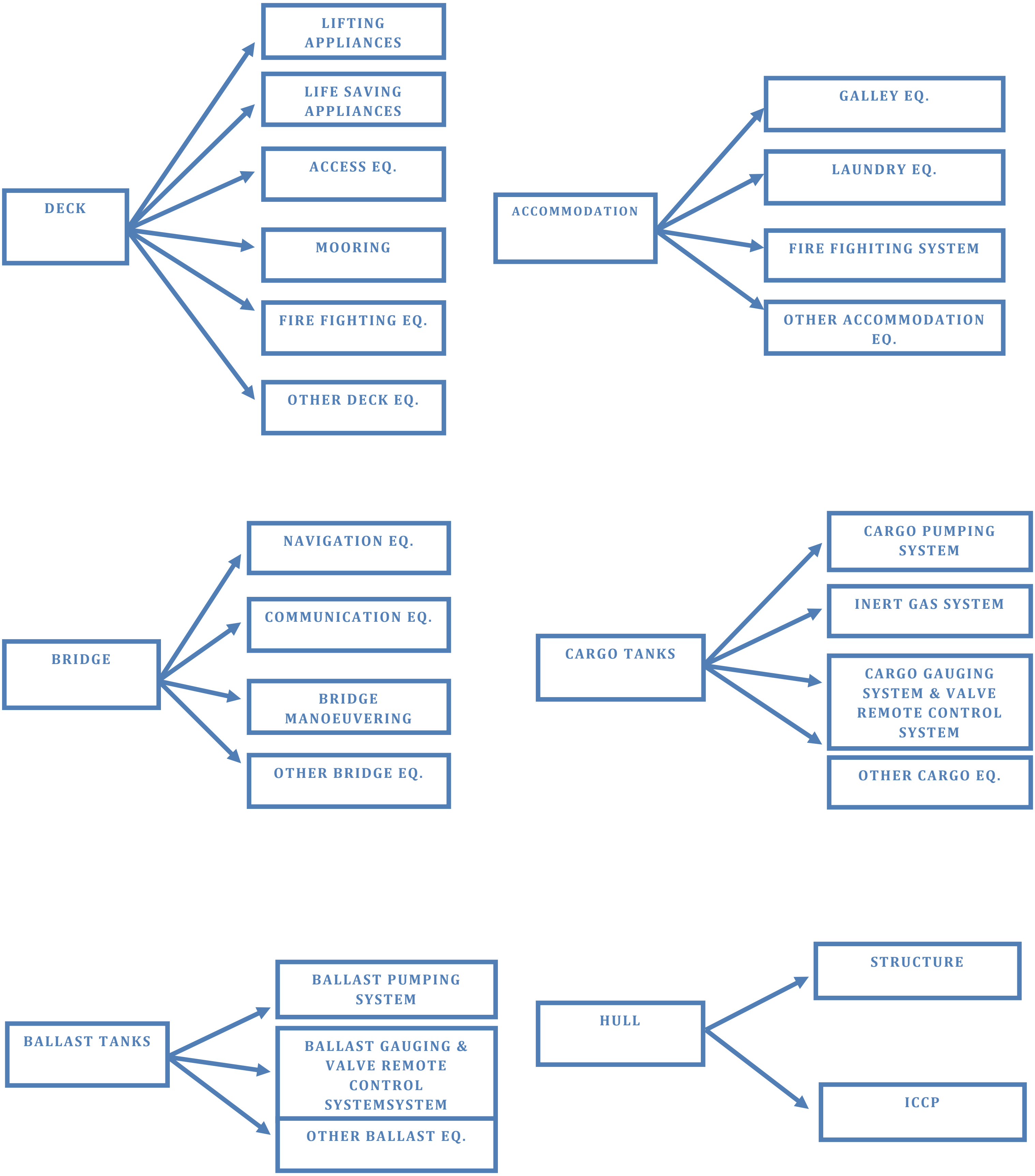

Figure12b: Subcategories of the Deck, Accommodation, Bridge, Cargo Tanks, Ballast Tanks, Hull

Through this analysis the figures that are presented below were created along with brief comments for the major classes of each subcategory.

3.3.1 Engine Room Subcategories

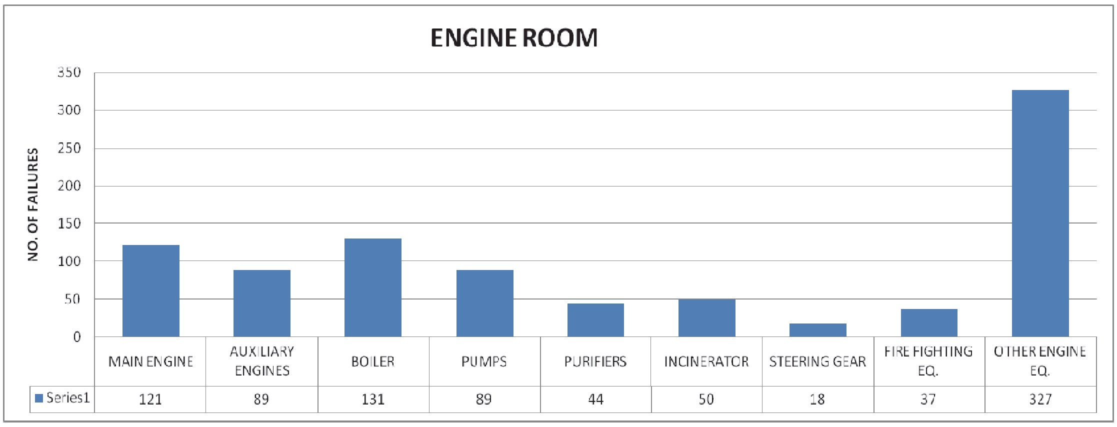

Figure 13: Number of failures for each category of the engine room regarding the entire fleet

1. Boiler: Most of the failures refer to the electrical equipment of the boiler, the control panel, multiple sensors, burner's electrodes. Also the fuel oil pumps of the boiler as well as the solenoid valves are prone to malfunctions.
2. Main Engine: Is the most crucial machinery as is responsible for the propulsion of the vessel. After the boiler comes second to failures and most of them refer to its safety and monitoring system and the fuel oil system.
3. Auxiliary Engines: All the examined vessels have three auxiliary diesel engines and their functionality is crucial for the vessel since a black out occurrence can have catastrophic results. As the main engine most of the malfunctions were about the safety and monitoring system and the fuel oil system of the engines.
4. Pumps: In the engine room is located a variety of pumps each one servicing a different role and system, such as the fresh water, bilge, cooling sea water, lube oil or fuel oil system. All the pumps located in the engine room except of the pump of the main engine, diesel engine, boiler, cargo and ballast pumps are included in this category. The data present frequent failures of the seal and the electrical motors.
5. Purifiers: In this category are included the fuel oil and the lube oil purifiers. The majority of the defects concern the fuel oil purifiers, there is a variety of failures like wear and tear of internal elements such as o-rings.
6. Steering Gear: The efficiency of performance of steering gear is essential for the vessel and there are standard requirements that must be adhered to. There are frequent inspections of the steering gear mechanism and this is the reason of the small number of failures. Defective sensors and contactors are the largest part of the failures.

7. Fire Fighting Eq.: This category contains mostly malfunctions of the smoke and heat detection system.
8. Other Engine Eq.: The rest of the machineries located in the engine room are inserted in this category. Is the category with the most failures, however if one examines each machinery separately the number of the failures are insignificant in comparison with the others. Here belong defects of the heaters, coolers, valves, bilge separator, air conditioning system, fresh water generator etc.

3.3.2 Deck Room Subcategories

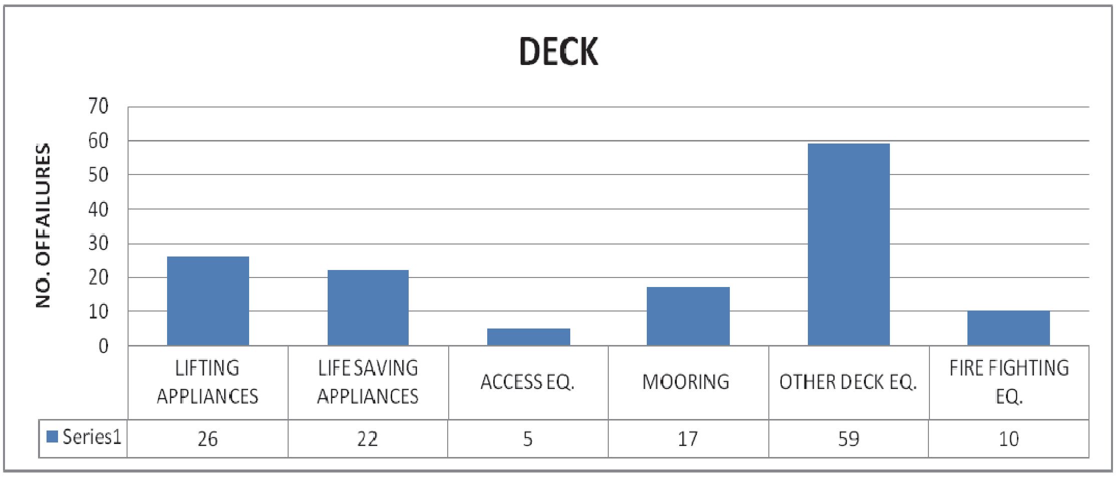

Figure 14: Number of failures for each category of the deck regarding the entire fleet

1. Lifting Appliances: The majority of the defects apply to the hose handling and the provision cranes and indicate problems to the hydraulic cylinders, the flexible hoses and the winches.
2. Life Saving Appliances: The life and rescue boats along with their davits consist this category. Regular malfunctions are presented in davit's winches and boat's diesel engine.
3. Access Eq.: In this category belong failures of the pilot, pilot rope and accommodation ladders and their mechanisms.
4. Mooring: The mooring arrangement includes failures of the windlasses and the mooring winches, with most common those regarding the brake lining and the hydraulic motor.
5. Fire Fighting Eq.: Defects of the deck fixed fire fighting system, of the hoses, and the deck fire line are included in this category.
6. Other Deck Eq.: The other deck equipment is a category of bulk defects like regarding deck lights, piping and valves, corrosion and general appearance of the deck.

3.3.3 Bridge Subcategories

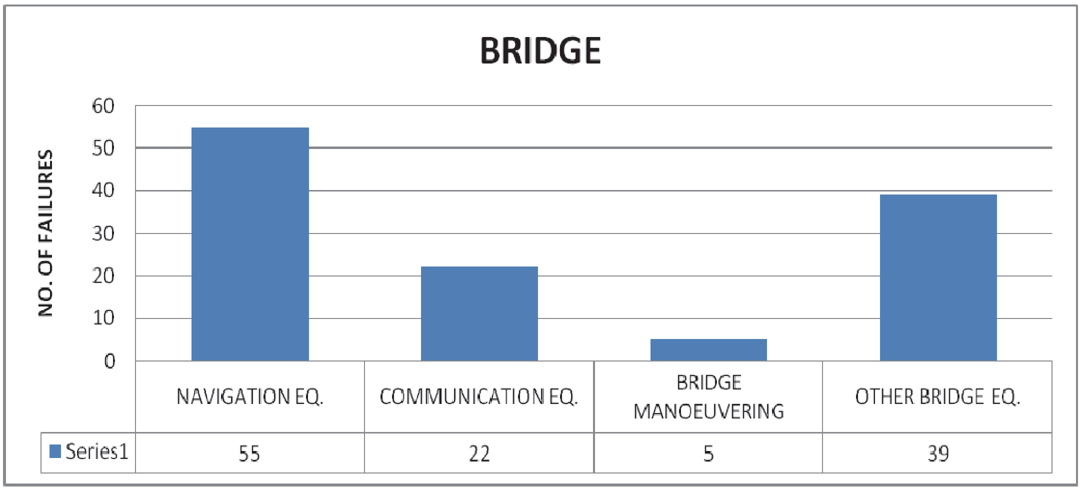

Figure 15: Number of failures for each category of the bridge regarding the entire fleet

1. Navigation Equipment: The instruments with purpose to ascertain the ship’s speed, direction and position like magnetic and gyro compass, radars, voyage data recorder (VDR), ECDIS.
2. Communication Equipment: The instruments for radio communication at sea and inside the vessel like global maritime distress and safety system (GMDSS), MF/HF radio, public address and auto exchange telephone system.
3. Bridge Manoeuvring: There only five failures in this category and there are for the batteries of the system and malfunction of the software.
4. Other Bridge Eq.: This category includes mostly problems of the window wiper and clear view screen system, of the anemometer, the anemoscope and the main console.

3.3.4 Ballast Tanks Subcategories

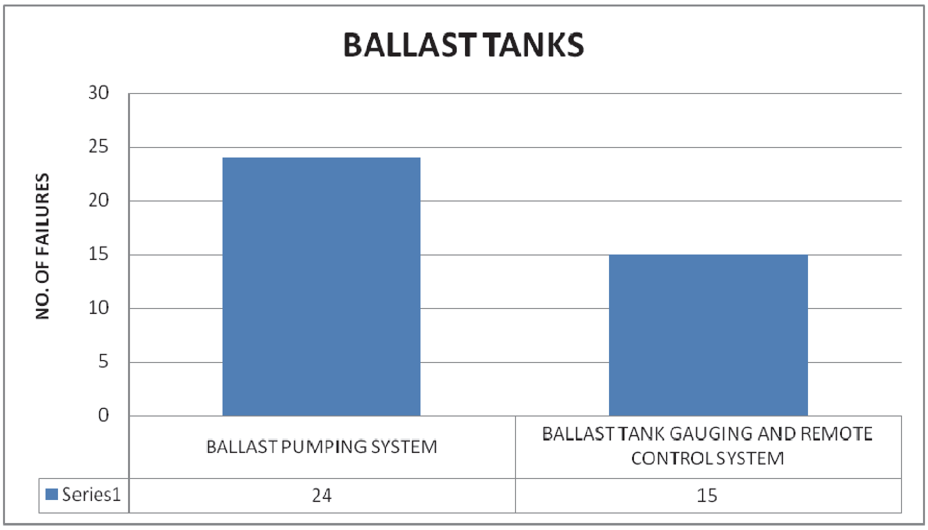

Figure 16: Number of failures for each category of the ballast tanks regarding the entire fleet

1. <u>Ballast Pumping System:</u> Consisted by the ballast pump, hydraulic valves, piping, monitoring and operation system. Most common failures of the ballast pump monitoring and operation system instead of the mechanical equipment.
2. <u>Ballast Tank Gauging and Valve Remote Control System:</u> Implementing remote tank level measurement of ballast and level monitoring, sensors are prone to malfunctions.

3.3.5 Cargo Tanks Subcategories

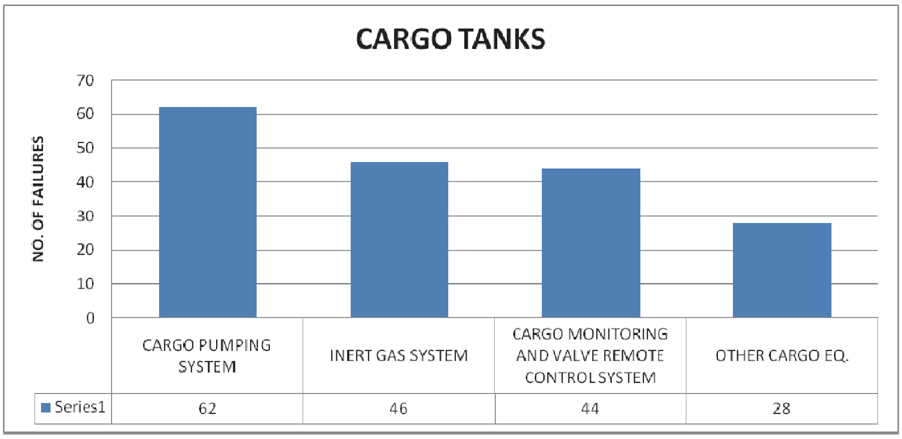

Figure 17: Number of failures for each category of the cargo tanks regarding the entire fleet

1. Cargo Pumping System: Consisted by submerged vertical centrifugal pumps for all the fleet powered by diesel power packs, the valves, piping, monitoring and operation system. The failures on this system are not concerted to a certain equipment.
2. Inert Gas System: Consisted by the gas producer and the scrubbing system, the isolating valves, oxygen analyzer and safety and monitoring equipment. The failures on this system are not concerted to a certain equipment.
3. Cargo Monitoring and Valve Remote Control System: Implementing remote tank level measurement of cargo, temperature, pressure readings and level monitoring, sensors are prone to malfunctions.
4. Other Cargo Eq.: The other cargo equipment failures are mostly for the tank cleaning machines, gas freeing fans and portable oxygen analyzers.

3.3.6 Accommodation Subcategories

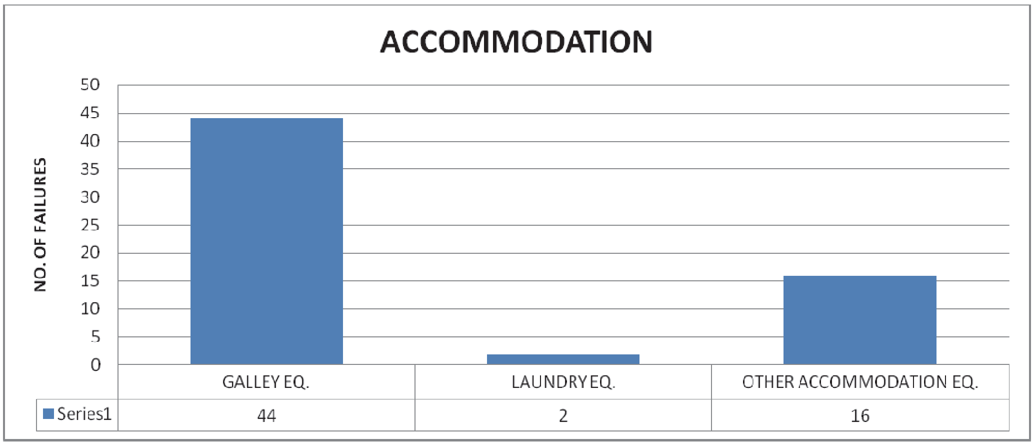

Figure 18: Number of failures for each category of the accommodation regarding the entire fleet

1. Galley Equipment: Defects are referring to the equipment which located in the galley such as the cooking ranges, exhaust fan, etc.
2. Laundry Equipment: This category contains two defects for the washing machines.
3. Other Accommodation Eq.: Most of the defects in this category are for the lighting fixtures, monitors, defective doors etc.

3.3.7 Hull Subcategories

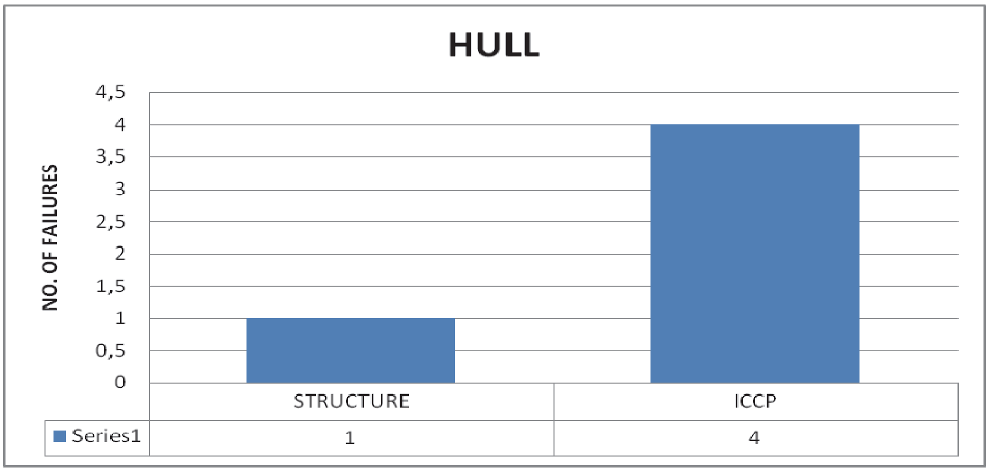

Figure 19: Number of failures for each category of the hull regarding the entire fleet

1. <u>ICCP/Structure:</u> The number of data in this category is very small, except of one defect regarding to plate deformation the other ones are for the impressed current cathodic system of the ship which is an arrangement of hull mounted anodes connected to the control panel in order to suppress the electro chemical reaction on the hull surface.

3.4 Main Engine and Auxiliary Engines Analysis

The four categories which appear to have the most failures are the boiler, main engine, auxiliary engines and pumps. In continuation of this analysis the main engine and auxiliary engines are going to be studied in depth. The reason that the other two categories were excluded is the lack of sufficient data regarding the exact time of the malfunctions since their maintenance schedule is based on calendar periods and not running hours. In addition regarding the boiler most of the failures were about the safety and monitoring system meaning that these components/parts cannot be checked or repaired since the end of their lifetime.

A system is an aggregate of sub systems consisting by components and parts. In this case the system which is described is the main and auxiliary engines. The coexistence and cooperation of these subsystems make the engines run and each component and part plays a significant role to make this happen. Despite the difference between these engines such as the size, strokes, load and revolution they are both diesel combustion ignitions engines with camshaft and their operation is similar and their main subsystems can be described simultaneously.

Fuel oil system: It can be divided in two systems fuel supply system and fuel injection system. The fuel supply system is dealing the transfer of the fuel and the injection system for the correct amount and timing of the injecting fuel in the combustion chamber. Includes pumps, nozzles, plungers, various piping (Babicz, 2015).

Lubricating oil system: Lubrication is essential for the engine, the internal parts create friction and heat which may have catastrophic results, applying lubricant oil provides cooling and debris removal as well. A variety of components as pumps, coolers, thermostatic valves and piping are included in this system (Kantharia, 2010).

Starting air system: In order the engine to start high pressure compressed air is supplied into the cylinders with the correct firing order. For this operation except of the main starting valve which is controlled by pilot valves located in the air distributor each cylinder has one starting valve. More than one starting valve remain open ensuring that the engine will start in any positions of the cylinders ("MachinerySpaces.com," 2010-2016).

Cylinder unit: As a cylinder unit here is defined the arrangement of the cylinder cover, cylinder head and the exhaust valves, the cylinder liner and the piston and piston rod which makes a reciprocating movement turning the thermal energy to kinetic.

Cooling water system: Is a circulated system for the cooling of the engine since the long run of the machinery produces great amount of heat. In that way the parts of the engine are protected from the high temperatures. The system uses fresh water which is cooled using the sea water as cooling agent via heat exchangers.

Turbocharger: Is very important machinery making possible to improve the efficiency of the engine supplying charge air to the combustion chamber using the exhaust gases of the combustion in order to turn the compressor.

Air cooler: Is located between the turbocharger and the cylinder unit and its purpose is to control the temperature of the air coming through the scavenge air ports to combustion chamber.

Auxiliary blower: Is electrically driven and provides initial charging air when the engine is starting till is reaching a curtain point of revolution.

Filter unit: In order to remove impurities and debris which can damage the parts of the engine like bearings, piston rings, cylinder liners oil filters are used. The most common types are fine mesh screen filter and auto backwash filter and are located in lube oil and fuel oil line both on suction and discharge side.

Mechanical control system: It can be described as the arrangement of the chain and chain drives, the camshaft and its bearings.

<u>Pneumatic system:</u> Is a compressed air system for the operation of the automation controls of the engine.

3.4.1 Main Engine Failures

The pre described subsystem of the diesel engines has set the background for the next analysis. The failures of the main engine have been separated to 12 categories. These categories were chosen and named according to the maintenance plan and the instructions manual of the manufacturer.

Almost all the categories have been described in the previous chapter. Nonetheless the cylinder unit has been divided to three categories the “cylinder liner & lubrication”, the “cylinder cover” and the “exhaust valve” following the maker’s plan.

In addition in the category “safety/monitoring equipment” are included all the sensors, thermometers, pressure stats, etc. which indicate locally or in the engine control room the reading of their measurement point and allow the monitoring and protection of the engine. At last the “hydraulic tools” are special tools for the main engine.

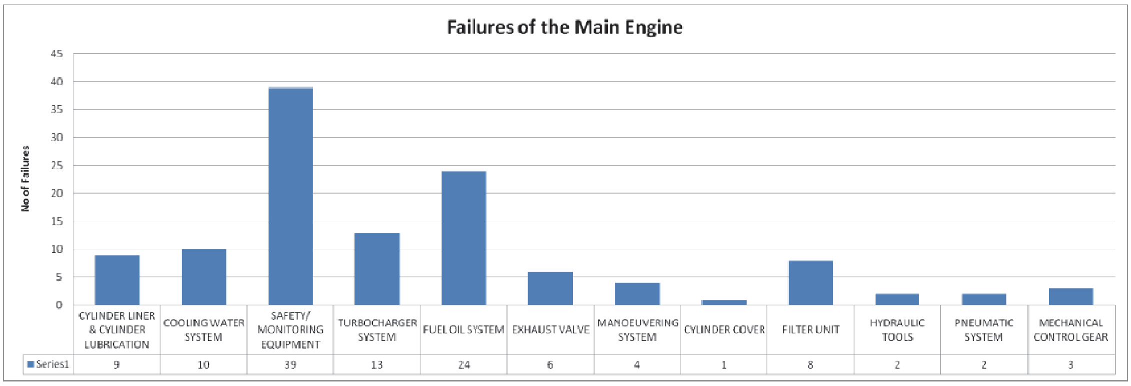

Figure 20: Number of failures for each category of the Main Engine

Figure 20 illustrates the number of the failures per category of the main engine. Since in this analysis the main scope is to analyze the most prone to malfunctions system it is observed that the categories with the most defects are the “safety/monitoring equipment” and the “fuel oil system”.

Despite the fact that the “safety/monitoring equipment” has more failures, the lack of data from operational hours till failure and the reason that they are not repairable make this category inappropriate for further analysis For that reason and in addition with the significance of system for the engine’s operation and the great risk of potential failures (Wabakken, 2015) such as engine misfire, knocking, insufficient power output or even cause a complete engine breakdown (Tian Ran Lin, 2011) the fuel oil system is going to be analyzed in furtherance.

3.4.2 Auxiliary Engines Failures

The same procedure, following the manufacturer's maintenance plan and instruction manual, was used to divide the categories of the auxiliary engines' failures.

All the categories have been already described, however, has to be mentioned that the cylinder unit has been separated to "exhaust valve" and "piston & connecting rod".

The next chart (Figure 21) shows the defects of each category. The two major in failures categories are like before the "safety/monitoring equipment" and the "fuel oil system".

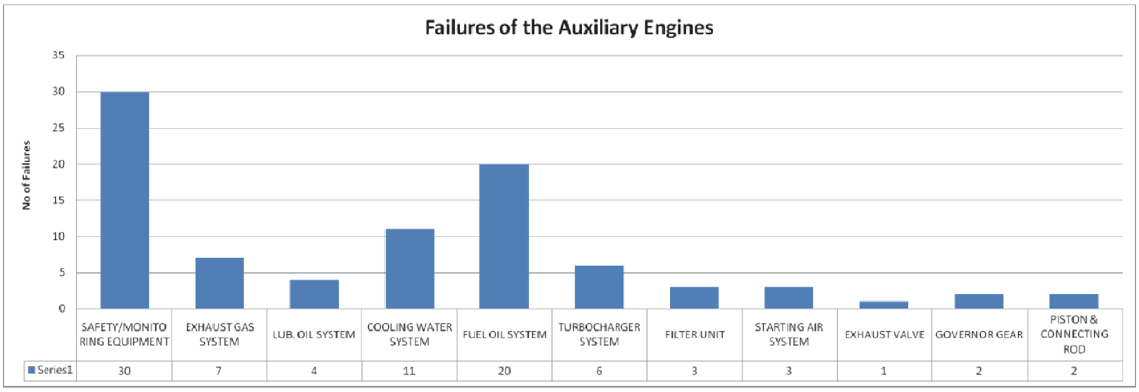

Figure 21: Number of failures for each category of the Auxiliary Engines

The two major in failures categories are like before the "safety/monitoring equipment" and the "fuel oil system". For the same reason as before the fuel oil system was chosen for further research.

3.4.3 Fuel Oil System

Fuel oil system is fundamental for the engine's function, the correct injection timing, the appropriate atomization of the fuel, the right viscosity and pressure are factors that improve the efficiency of a diesel engine.

In the marine industry heavy fuel oil is the most common type of fuel, however in order to be used needs special treatment to clear away the impurities and the water content that contains. The heavy fuel oil is stored in tanks and is pumped to the settling tank and heated, after through the feed pump flows to the purifiers where through a centrifugal process is being cleaned and then pumped to the service tank. From the daily service tank goes to the filter unit and next passes through the flow meter, fitted to indicate the fuel consumption, and from a three way valve reaches the mixing tank. At last the circulation pumps lead the fuel to the heaters, viscosity controller in order to reach the appropriate conditions and ends up to the engine. The dirty fuel or sludge is stored in the sludge tank (Kleimola, 2006).

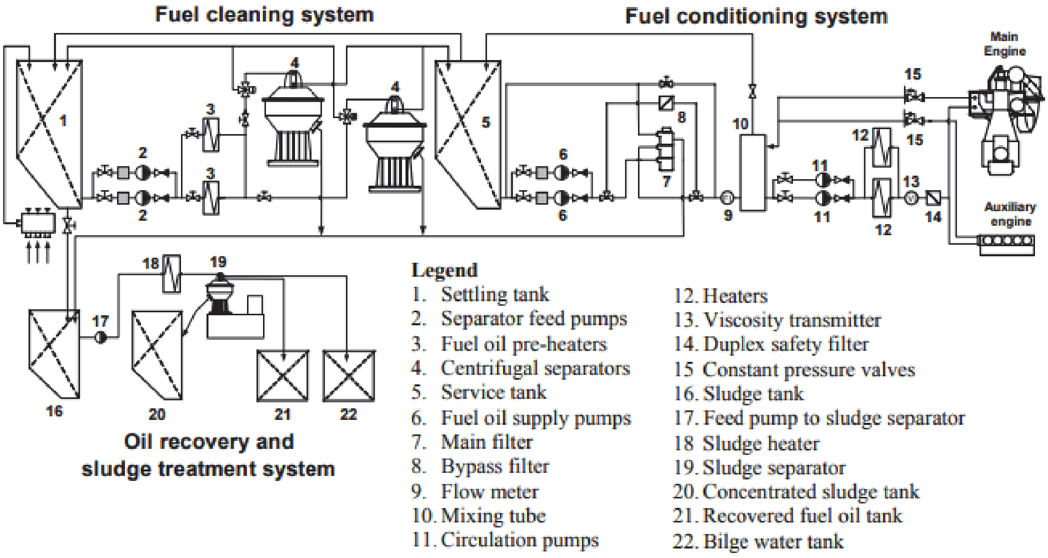

Figure 22: Fuel oil treatment system

When fuel reaches the engine the fuel oil system of her is responsible for the procedure of injection in the correct timing. The pumps are mechanically driven by cams mounted on the camshaft which is driven by the crankshaft. Inside the pump exists the plunger which is a spring loaded ram and moves in a reciprocating process, as the cam rotates, within a matching cylinder called barrel. The fuel inserts from the suction valve through a port and is pressurized when the plunger moves up, beginning the compression, afterwards via the delivery valve assembly which is mounted in the top of the housing goes to the fuel valve where the atomization takes effect and enters the combustion chamber.

In order to adjust the timing of the injection and hence achieve fuel economy many engines have a variable injection timing system (VIT) or the modern electronically engines have sensors and the fuel pumps are independent from the crankshaft position meaning that the fuel injection timing and quantity can be programmed separately to each cylinder ("www.marinediesels.co.uk ").

4 THEORITICAL BACKROUND OF RELIABILITY ANALYSIS

This chapter sets the basis for the deeper understanding of the following reliability analysis. Significant meanings and methods are being described briefly in theoretical and mathematical terms.

4.1 Frequency distribution

Frequency can be defined as the number of occurrences of a value in a specified data set. In statistics the frequency distribution is the tool that provides the quantitative information of the observed occurrences or possible outcomes of an event in tabular or graphical format.

A frequency table depicts the number of observations in each category that the sample has been divided. These categories are called class intervals and their selection usually depends on the analyst and the size of the data. If these classes are too many then the data reduction is not being achieved, at the same time if there are few the distribution of the data cannot be easily determined (Manikandan, 2011).

4.2 Histogram

A histogram is a plot similar to a bar chart representing the frequency distribution of numerical data. The man behind this idea is Karl Pearson and gave the name histogram in 1981 explaining that this diagram could be used as tool studying historical time periods (Rufilanchas, 2017). The main difference between a histogram and a bar chart is that the first relates two variables while the second only one.

Building a histogram needs to “bin” the continuous data into classes, the divided intervals can be of equal size or not. Then each class contains a certain amount of values producing the chart. In case the bins have equal sizes then the diagram shows the frequency of each one, in the other case when the width of the bins is uneven the vertical axis is shown the frequency density and the horizontal the population.

The optimal selection of the classes is given by the following formula (Sturges, 1926):

$$C = \frac{R}{1 + 3.322\ logN}$$

Where R is the range and N the size of the sample.

4.3 Box Plot Diagram

The box plot diagram or box and whiskers plot is first described by Tukey in 1977. This statistical method of interpretation tabular data is very useful to visually summarize and identify variations in data groups (Dawson, 2011).

A box plot is constructed by a rectangular box vertical or horizontal which upper end is the upper quartile and the bottom end the lower quartile and represent the 25th and 75th percentile respectively. The box inside the two quartiles stands for the 50% of the sample and the line inside it is the median, its position shows the skewness of the data (David F. Williamson, 1989).

Outside of the box there are two lines in both ways and are known as whiskers. The whiskers may be even or not depending of the symmetry of the data, same size lines means symmetrical data and the opposite. The area between the whiskers is called inner fence and the 95% of the observation are included there.

The other area which almost is never marked is being called outer fence and includes the 99% of the observations.

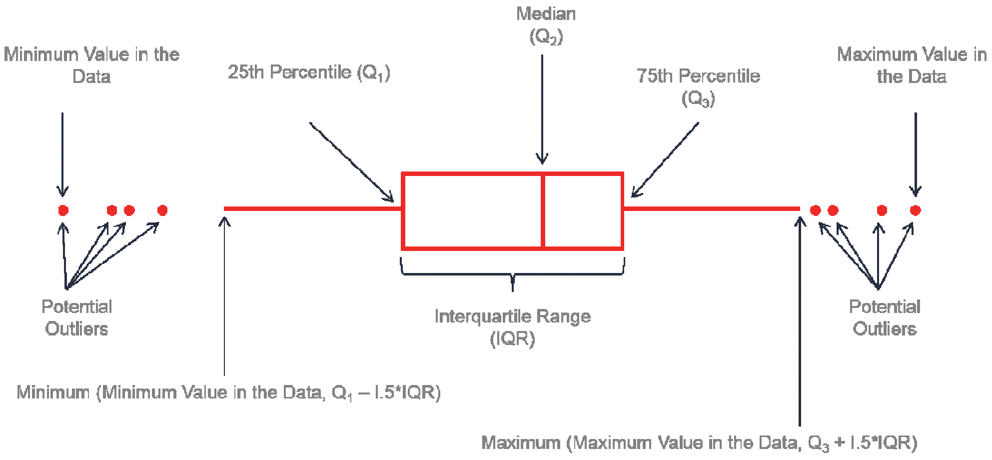

Figure 23: Box plot diagram example

The limit points that specify these areas can be calculated as below:

- lower inner fence: Q1 - 1.5*IQR
- upper inner fence: Q3 + 1.5*IQR
- lower outer fence: Q1 - 3*IQR
- upper outer fence: Q3 + 3*IQR

The great advantage of this technique is that outlier data can be identified. As outliers are considered all the values that deviate notably from the others among a group of data and can influence the results of the analysis (Manikandan, 2011).

In the box plot analysis the observations which appear to be outside the inner fence, hence greater than the upper inner fence or minor that the lower inner fence are potential outliners and may be excluded from the analysis. Of course prior to eliminating these extremes of the analysis one should try to appreciate why these data exist and if they create a pattern.

4.4 Probability Functions

For a continuous variable a probability density function (PDF) connects any given variable (or space) in the data sample with a relative likelihood probability range within the particular distribution and is designated as f(t).

The cumulative distribution function (CDF) is an alternative way to describe the distribution of a random variable. It is connected with the PDF as its integral and shows the probability the data sample to be less or equal than the given variable (Arora, 2016).

The two functions are connected with the following equation:

$$F(t) = \int_{0}^{t} f(y)dy \,, 0 \leq t < \infty$$

Another aspect, valuable in reliability analysis, is to know the probability that an object of interest has not yet occurred in a specified time, this information is given by the survival function which is explained mathematically below:

$$S(t) = P\left(\{T > t\}\right) = \int_{t}^{\infty} f(y)dy \; = 1 - F(t)$$

The hazard function which can be described as a measure of risk even though is not a probability or density it can be considered so. Practically gives the microscopic time period where the opportunity of an event’s occurrence has its lowest or highest values and is defined as the ratio of probability density function to survival function (John P. Klein, 1997).

$$h(t) = \frac{f(t)}{S(t)}$$

The cumulative hazard function or integrated hazard function is not a probability too and is given as follows:

$$H(t) = \int_{-\infty}^{t} h(y)dy$$

4.5 Basic Concepts and Probability Distributions

4.5.1 Parametric Analysis

In parametric analysis the data resembled by a matching distribution describing the density of the sample and has a fixed set of parameters. A common assumption among the parametric methods is that the spread of the data variances across the range of the sample and is homogeneous (Douglas G. Altman, 2009).

Two of the most well known distributions that are used in parametric methods are the Normal and Weibull distributions which are analyzed below.

4.5.1.1 Normal Distribution

It is the most common distribution of all in the statistics and is applied to more than one field to describe many types of data. It is also known as the bell curve or the Gaussian distribution and is based on the central limit theorem.

The normal probability density is:

$$f(t) = (1/\sigma)(2\pi)^{-1/2} \exp\left[-\frac{(t-\mu)^2}{2\sigma^2}\right], \quad -\infty < t < \infty$$

And the normal cumulative density function is:

$$F(t) = P\{T \leq t\} = \int_{-\infty}^{t} (2\pi\sigma^2)^{-1/2} \exp\left[-(t-\mu)^2/(2\sigma^2)\right]dt, \qquad -\infty < t < \infty$$

Where μ is the mean and can have any value and the parameter σ is the standard deviation and is positive (I.E.Hoffman, 2019).

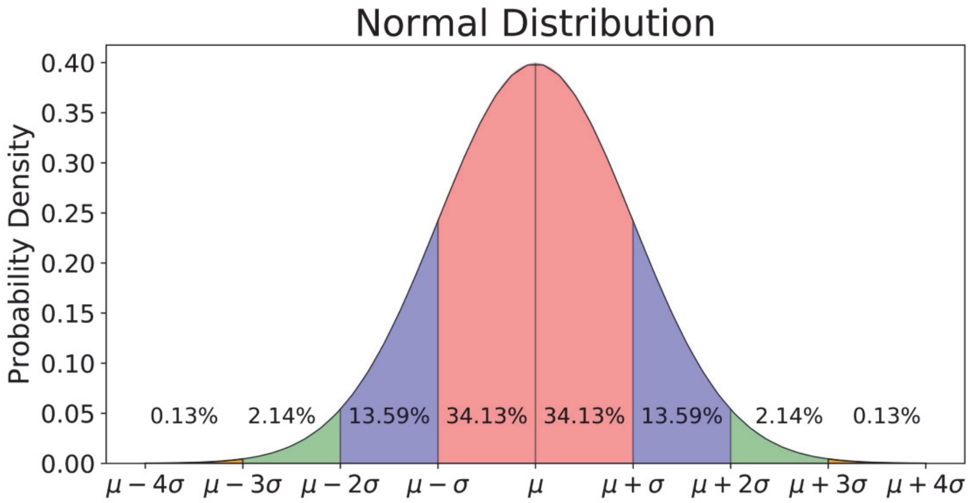

Figure 24: Probability density function of Normal distribution

The Figure 24 depicts the probability density which is symmetric and as can be seen most of the observations are gathered around the mean value (Monica Franzese, 2018).

4.5.1.2 Weibull Distribution

Weibull is a continuous probability distribution and is commonly used for life data and product reliability assessment. Its name came from the Swedish mathematician Waloddi Weibull who defined in detail this method in 1951. The flexibility to fitting data makes the Weibull distribution a valuable tool in reliability analysis.

In continuation are mathematically described the most important functions and parameters of the distribution.

- The probability density function: $f(t) = (\beta/\alpha^{\beta})t^{\beta-1}\exp\left[-(t/\alpha)^{\beta}\right], \quad t > 0$

Where the parameter α is called scale parameter and the parameter β shape parameter are both positive.

- The probability cumulative function: $F(t) = 1 - \exp\left[-(t/\alpha)^{\beta}\right], \quad t > 0$

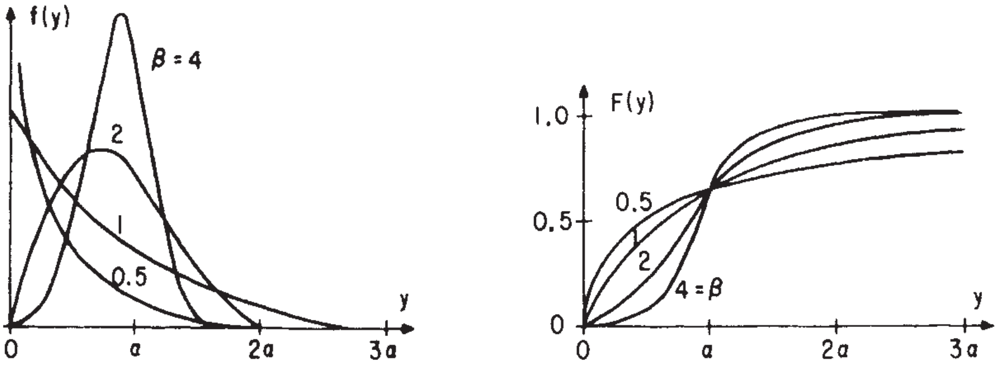

Figure 25: Probability density function (left diagram) and cumulative function (right diagram) of Weibull distribution

The above figures present the graphs of density cumulative functions. For β=1 the Weibull distribution becomes the exponential distribution. For β=2 is known as Rayleigh distribution and for $3 \leq \beta \leq 4$ approaches the normal distribution (Nelson, 1982).

- The probability hazard function: $h(t) = (\beta/\alpha)(t/a)^{\beta-1},\ t > 0$

- The mean value: $E(t) = a\Gamma\ [1 + (1/\beta)]$,

where Γ is the gamma function $\Gamma(u) = \int_0^\infty z^{u-1} \exp{(-z)}$

- The variance: $Var(t) = a^2\{\Gamma\ [1 + (2/\beta)] - \{\Gamma[1 + (1/\beta)]\}^2\}$

- The standard deviation: $\sigma(t) = \alpha\{\Gamma\ [1 + (2/\beta)] - \{\Gamma[1 + (1/\beta)]\}^2\}^{1/2}$

4.5.2 Non Parametric Analysis

Many times safe assumptions regarding the fit of a normal distribution in a set of data cannot be made, in such cases the observations can be considered as distribution free or that follow a certain distribution but its parameters are not fixed. This is the other fundamental principle of statistics which have gained appreciation cause its simplicity and is called non parametric analysis.

Non parametric analysis co-occurs with descriptive statistics using the observed data to evaluate the parameters which describe the sample (Amandeep Kaur, 2015).

Assuming a sample of data with observations $x_1, x_2, \ldots, x_n$ and N the size of the sample the non parametric estimates can be expressed through the following mathematical statements.

- The sample mean: $\bar{x} = \frac{1}{N}\sum_{i=1}^{N} x_i$
- The sample standard deviation: $\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_{i-} \mu)^2}$
- The sample variance: $s^2 = \frac{1}{N-1}\sum_{i=1}^{N}(x_i - \bar{x})^2$
- The sample coefficient of variation: $CV = \bar{x}/\sigma$

When the sample is assembled from lifetime data, the way to acquire the distribution that describe the data is an empirical method and can be seen below (John Kalbfleisch, 2002).

$$F_n(t) = \frac{Number\ of\ lifetimes\ \le t}{n}$$

And the corresponding survival function is

$$R_n(t) = 1 - F_n(t) = \frac{Number\ of\ lifetimes > t}{n}$$

Since lifetime are usually distinct observations the two equations are increase and decrease respectively by a pace of 1/n before each following observation, something that is visible if they graphically represent (Jayant V. Deshpande, 2005).

4.5.2.1 Kaplan Meier Estimators

Edward L. Kaplan and Paul Meier joined their efforts in 1958 and presented a method for non parametric estimation from incomplete observations. The main idea was to estimate the survival function or the observations that survived from the occurrence of an event with distinct starting and ending point, without assuming a predefined distribution for the sample (Edward L. Kaplan, 1958).

The Kaplan Meier estimator or product limit estimator can be written as:

$$\hat{S}(t) = \prod_{t_i \le t} \left[1 - \frac{d_i}{n_i}\right]$$

To understand the above expression t_i is the time that an event happened (e.g. a component failure) d_i is the count of the occurred events at time t_i and n_i the observations that have not failed till this time.

In addition the cumulative hazard distribution which gives as the rate of hazard over time is (Arthur V. Peterson, 1977):

$$\widehat{H}(t) = -\ln\,(\widehat{S}_t)$$

4.6 Goodness of Fit

The Goodness of Fit of a statistical model defines how well an assumed distribution describes a set of data. This technique uses asymptotic methods from the statistical hypothesis testing to compare the observed values and the expected values of a known probability distribution. Assessing absolute distribution fit to the observations is crucial in reliability analysis as conclusion drawn on incorrect fitting models may be ambiguous (A. Maydeu-Olivares, 2010).

4.6.1 Chi Square Goodness of Fit

The chi square goodness of fit examines if a set of data is part of a population described by a specific distribution.

The observed distribution of the sample is compared with the expected probability distribution. One of the features of this method is that can be applied to any univariate distribution which the cumulative distribution function can be calculated.

The sample data are divided into interval or in other terms the data must be binned then the numbers of the observations that fall into the bin are compared with expected number of observations in each bin.

The disadvantages of the chi square goodness of fit are that requires a sufficient sample size for the estimation to be valid and also that is depended on how the data are binned (McHugh, 2013).

The chi square test is defined by the hypothesis:

A) **Null hypothesis:** assumes that there is no significant difference between the observed and the expected value.
B) **Alternative hypothesis:** assumes that there is a significant difference between the observed and the expected value.

Hypothesis Testing: The sample data are divided into k bins and the values are calculated using the following formula:

$$x^2 = \sum_{i=1}^{k} (O_i - E_i)^2 / E_i$$

The observed frequency for bin i is called O_i and the expected E_i.

The expected frequency is calculated as:

$$E_i = N(F(Y_u - F(Y_l))$$

Where F is the cumulative distribution function, Y_u and Y_l are the upper and lower limit for class I and N the size of the sample.

The chi squared distribution has (k − c) degrees of freedom, where k is the number of non empty cells and *c* is the number of estimated parameters for the distribution plus one. The critical value of chi square with significance *a* and degrees of freedom *k-c* is $x^2_{1-a,k-c}$ and if the following apply

$$x^2 > x^2_{1-a,k-c}$$

the data are not coming from a population with specified distribution.

4.6.2 Kolmogorov-Smirnov Test

The Kolmogorov-Smirnov test which is another widely known goodness of fit test in comparison with the chi square needs a smaller size sample of data to make valid assumptions, however though other test may be more sensitive if the data meet their requirements.

The test quantifies the difference between the calculated empirical distribution function of the sample and the cumulative distribution function of the reference distribution. More specifically, the test compares a known hypothetical probability distribution to the distribution generated by the given observations which is considered under the null hypothesis either continuous either purely discrete either mixed. When the test refers to two samples the given distribution is considered under the null hypothesis continuous but unrestricted.

The Kolmogorov-Smirnov test is defined by the hypothesis:

A) The data follow a specified distribution.
B) The data do not follow a specified distribution

Hypothesis testing: Using the F which is the fully specified and continuous cumulative distribution function of the under examination distribution the Kolmogorov-Smirnov test is defined as:

$$D = max_{1\leq i\leq N}(F(Y_i) - i - \frac{1}{N}, \frac{i}{N} - F(Y_i))$$

If the statistic test D is greater than the critical value obtained from a table the hypothesis regarding the distributional form is rejected. There are several variations of these tables that use different scalings and critical regions. These alternative formulations should be equivalent but in the same way to establish that the statistic test is adapted to the estimation of the critical values (Carroll Croarkin, 2012).

4.6.3 Anderson Darling Test

A modification of the Kolmogorov Smirnov in order to test if a set of data came from a population with a determined distribution is the Anderson Darling test. The difference between these two tests is that the Anderson Darling gives more attention to the tails.

This method calculates the critical values of the specific distribution fitted to the data giving the advantage of a more trustworthy test. On the other hand the critical values must be calculated for each distribution and are depended on the distribution that being tested, currently though the tables of the critical values for the most known distributions like normal, Weibull, uniform etc. exist.

The Anderson Darling test is defined by the hypothesis:

A) The data follow a specified distribution.
B) The data do not follow a specified distribution

Hypothesis testing: Using the F which is the fully specified and continuous cumulative distribution function of the under examination distribution the Anderson Darling test is defined as:

$$A^2 = -N - S$$

Where

$$S = \sum_{i=1}^{N} 2i - 1/N(ln\, F(Y_i) + \ln{(1 - F(Y_{N+1-i}))})$$

If the value A is greater than the critical value the hypothesis that the distribution is of a specific form is rejected (Carroll Croarkin, 2012).

4.6.4 P-Value

At this point considered to be appropriate to define the calculated probability of the occurrence of an event or p-value, which determines the significance of the results within a hypothesis test (Goodman, 2008).

In hypothesis tests p-value is used to weigh the strength of the evidence or commonly to evaluate if the data are coming from a curtain population. It is a number between 0 and 1 and its values gives assumptions for the null hypothesis explained as following.

- P-value ≤ 0.05 indicates strong evidence against the null hypothesis and so can be rejected.
- P-value > 0.05 indicates weak evidence against the null hypothesis and so cannot be rejected.
- P-value ≈ 0.05 is controversial and safe assumptions regarding the null hypothesis cannot be made.

5 EXPERIMENTAL ANALYSIS

The previous chapter sets the theoretical background for the deeper understanding of the forthcoming analysis.

The outcome of the collected field data displayed that there is a high rate of failure appearance concerning the fuel oil system of the main and the auxiliary engines.

On this basis a study regarding the reliability of the two systems will support the preliminary observations and safer conclusions can be made. Both parametric and non parametric investigation can be applied so the essential distinct statistics are translated and comprehended and it is finished up whether these pursue a particular distribution.

For every individual failure the specific running hours till failure were acquired and will be examined for the main and the auxiliary engines separately.

5.1 Main Engine Fuel Oil System Failures

In the following table are presented the running hours of main engine’s components since the time to fail.

Table 3: Running hours of Main Engine's fuel oil system failures

15479	13820
13706	8628
10969	9097
3022	13979
2692	1341
8435	5270
7641	13140
10490	10164
9691	140
2064	6684
9750	4626
4199	6150

5.1.1 Box Plot diagram and Outlier points

A significant point to begin this analysis is to check the existence information for conceivable outliers which may generate misleading results. However, it is reminded that anomalies in the data often contain profitable data about the procedure under scrutiny of the information assembling and recording process. Prior to thinking about the conceivable end of these observations from the data one should endeavor to comprehend why they showed up and whether it is likely comparative qualities will keep on showing up (Clemens Reimann, 2005).

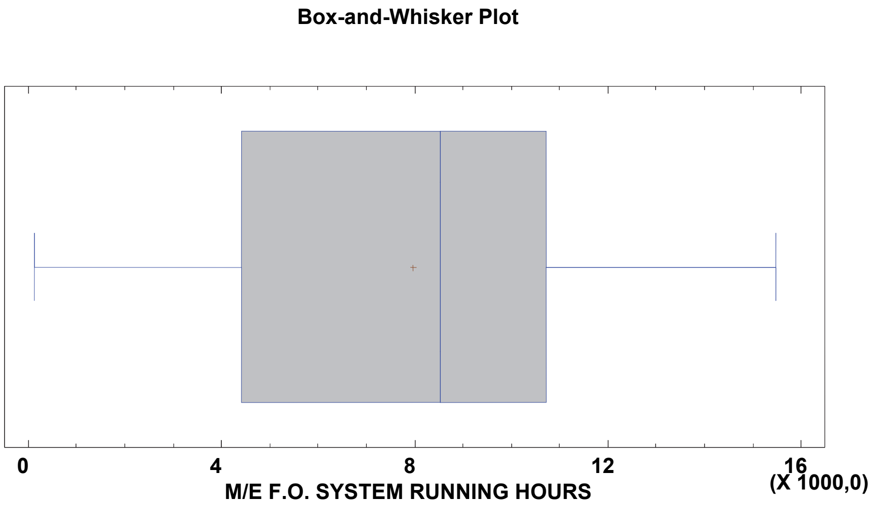

Figure 26: Box plot diagram of Main Engine's fuel oil system failures

Table 4: Summary statistics of Main Engine's fuel oil system failures

Count	24
Average	7965,71
Median	8531,5
Standard deviation	4397,6
Minimum	140
Maximum	15479
Range	15339
Lower quartile	4412,5
Upper quartile	10729,5
Interquartile range	6317

As indicating from the Figure 26 no possible outliers are observed.

The 24 values as Table 4 shows ranging from 140 to 15,479 and the median (Q2) of the data is 8,531,5. The 25th percentile (Q1) is 4,412,5 and the 75th percentile (Q3) is 10,729,5. Also the interquartile range (IQR) of the sample is 6,317.

5.1.2 Histogram

The frequency distribution of the data can be seen to the histogram below.

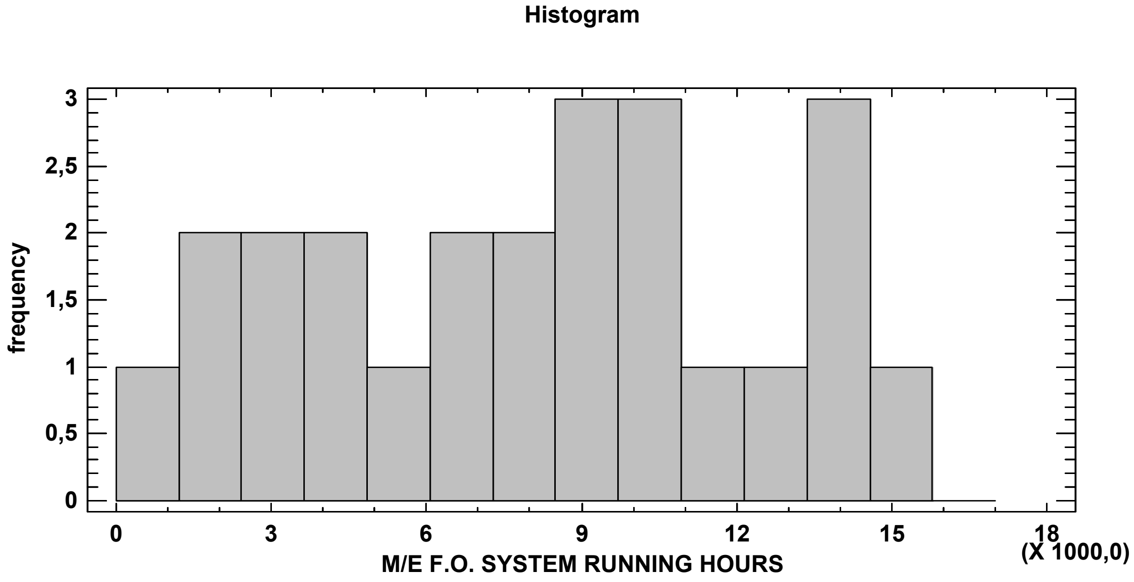

Figure 27 Histogram of Main Engine's fuel oil system failures

A frequency tabulation was created by dividing the range of the values into equal width intervals and counting the number of data values in each interval. The frequencies show the number of data values in each interval, while the relative frequencies show the proportions in each interval. This process is described in the table below.

Table 5: Frequency tabulation table of Main Engine's fuel oil system failures

Class	*Lower Limit*	*Upper Limit*	*Midpoint*	*Frequency*	*Relative Frequency*	*Cumulative Frequency*	*Cum. Rel. Frequency*
1	0	1214,29	607,143	1	0,0417	1	0,0417
2	1214,29	2428,57	1821,43	2	0,0833	3	0,1250
3	2428,57	3642,86	3035,71	2	0,0833	5	0,2083
4	3642,86	4857,14	4250,0	2	0,0833	7	0,2917
5	4857,14	6071,43	5464,29	1	0,0417	8	0,3333
6	6071,43	7285,71	6678,57	2	0,0833	10	0,4167
7	7285,71	8500,0	7892,86	2	0,0833	12	0,5000
8	8500,0	9714,29	9107,14	3	0,1250	15	0,6250
9	9714,29	10928,6	10321,4	3	0,1250	18	0,7500
10	10928,6	12142,9	11535,7	1	0,0417	19	0,7917
11	12142,9	13357,1	12750,0	1	0,0417	20	0,8333
12	13357,1	14571,4	13964,3	3	0,1250	23	0,9583
13	14571,4	15785,7	15178,6	1	0,0417	24	1,0000
14	15785,7	17000,0	16392,9	0	0,0000	24	1,0000

5.1.3 Non Parametric Analysis

As have already been mentioned non parametric analysis are normally utilized in designing applications since they are frequently sufficient and yield sufficient results for little samples.

Non parametric strategies do not require an assumption for a standard parametric structure of distribution for the data.

5.1.3.1 Non Parametric Estimates

The descriptive non parametric estimates of the population are presented in the table 6.

Table 6: Descriptive non parametric estimates of Main Engine's fuel oil system failures

Count	24
Mean	7965,71
Median	8531,5
Standard deviation	4397,6
Stnd. skewness	-0,14
Stnd. kurtosis	-0,98
Coeff. of variation	55,21%

These estimates were calculated from the failure data and are the basic measures describing them.

5.1.3.2 Empirical Cumulative Distribution

The empirical cumulative distribution function is step function with step 1/N extracted from the sample which has N size and since the data are uncensored the step is fixed. At any predetermined value of the measured variable is expressed the percent of the observations that have failed.

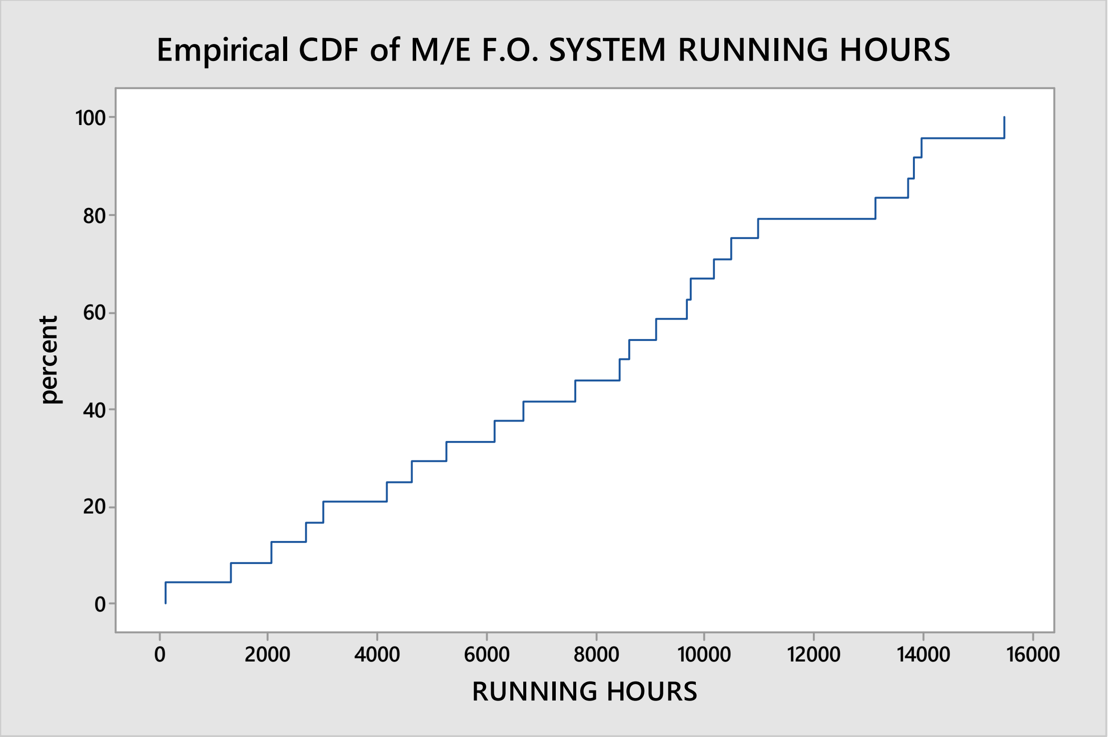

Figure 28: Empirical cumulative distribution function plot of Main Engine's fuel oil system failures

The empirical cdf is related with the genuine distribution of the data and various valuable conclusions can be raised, since it is a steady consistent estimator of the populace cdf.

For instance the 50% of the fuel oil system parts will have failed since the 8500 running hours (Figure 28).

5.1.3.3 Cumulative Failure Distribution

In continuation using the Kaplan Meier analysis the cumulative distribution function, the survival function and the cumulative hazard function for the sample are estimated.

The difference between the empirical cdf and the cdf is that the second is an estimation produced for the sample that the observations are coming from, however in this case since there are no censored observations the two plots are very similar. The empirical cdf is a discrete description of the data and for large sample is a good approximation of the cdf which is a theoretical construction (Chen, 2017).

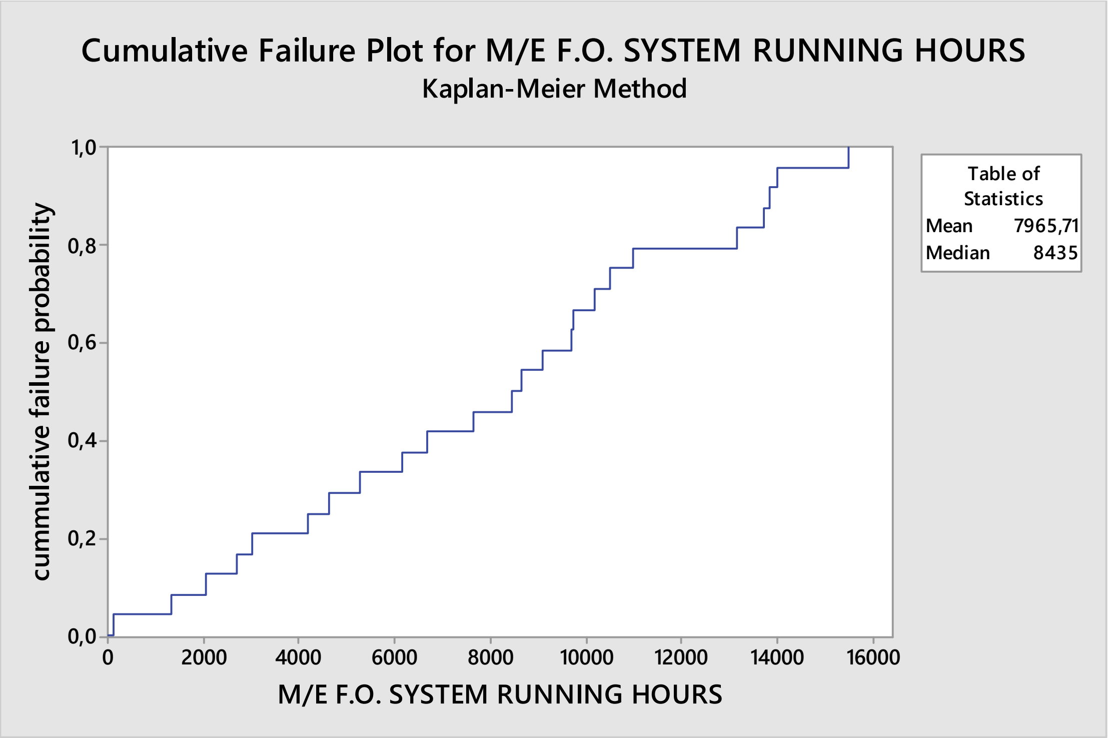

Figure 29: Cumulative distribution function plot of Main Engine's fuel oil system failures

The probabilities of the graph can be seen in table 7. In each time value is given the probability that a component will have failed since this time, the standard error is calculated as corrective factor. The probabilities are increasing with a steady step as the empirical cumulative distribution. It is also observed that the in 8,500 hours the probability of a component to break down is 0.5 meaning that there is 50% chance to have a failure in the system.

Table 7: Cumulative failure probabilities and standard errors of Main Engine's fuel oil system failures

Time	*Cumulative Failure Probability*	*Standard Error*
140	0,04	0,04
1341	0,08	0,05
2064	0,13	0,06
2692	0,17	0,07
3022	0,21	0,08
4199	0,25	0,08
4626	0,29	0,09
5270	0,33	0,09
6150	0,38	0,09
6684	0,42	0,10
7641	0,46	0,10
8435	0,50	0,10
8628	0,54	0,10
9097	0,58	0,10
9691	0,63	0,09
9750	0,67	0,09
10164	0,71	0,09
10490	0,75	0,09
10969	0,79	0,08
13140	0,83	0,08
13706	0,88	0,07
13820	0,92	0,05
13979	0,96	0,04
15479	1,00	0,00

5.1.3.4 Survival Distribution and Cumulative Hazard Plot

In the analysis of lifetime data, it is many times helpful to summarize the data in terms of the estimated survivor function. It is as the others a step function that decreases by 1/n at each observed failure time and indicates the probability that a failure has not yet occurred by a time t.

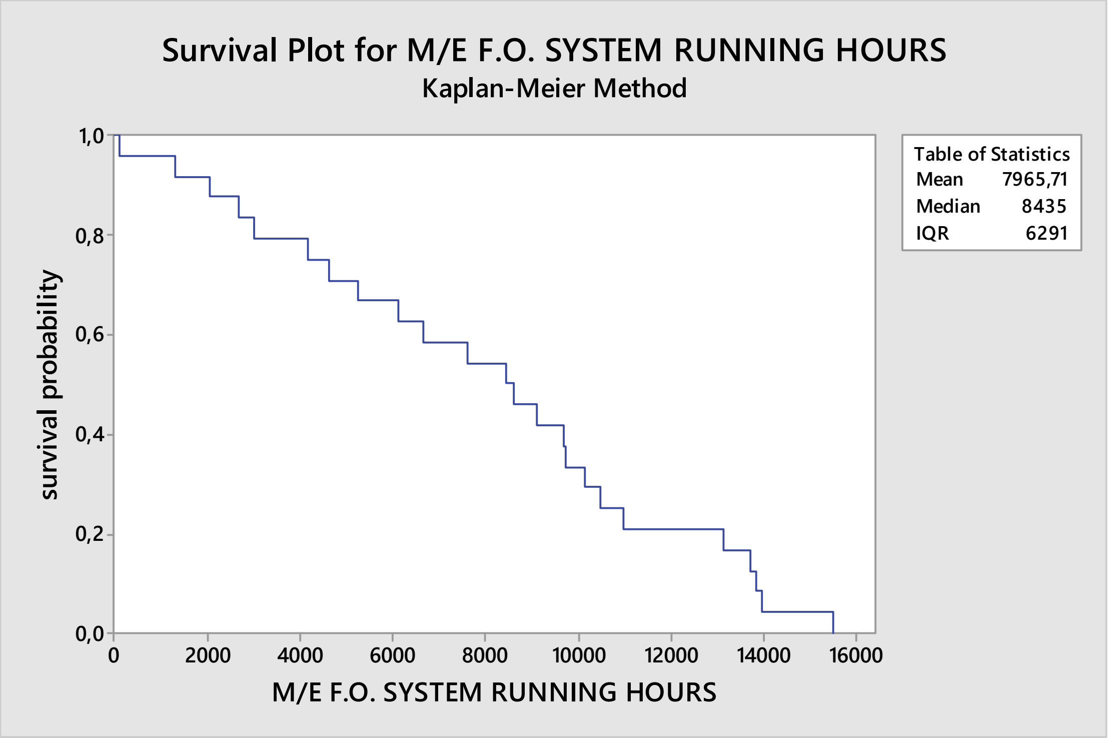

Figure 30: Survival function plot of Main Engine's fuel oil system failures

To begin with the horizontal lines in Figure 30 along the X-axis represent the survival duration for that interval. Each interval is determined by the previous and the next failure. The vertical distances illustrate the change in the cumulative survival probability as the curve advances.

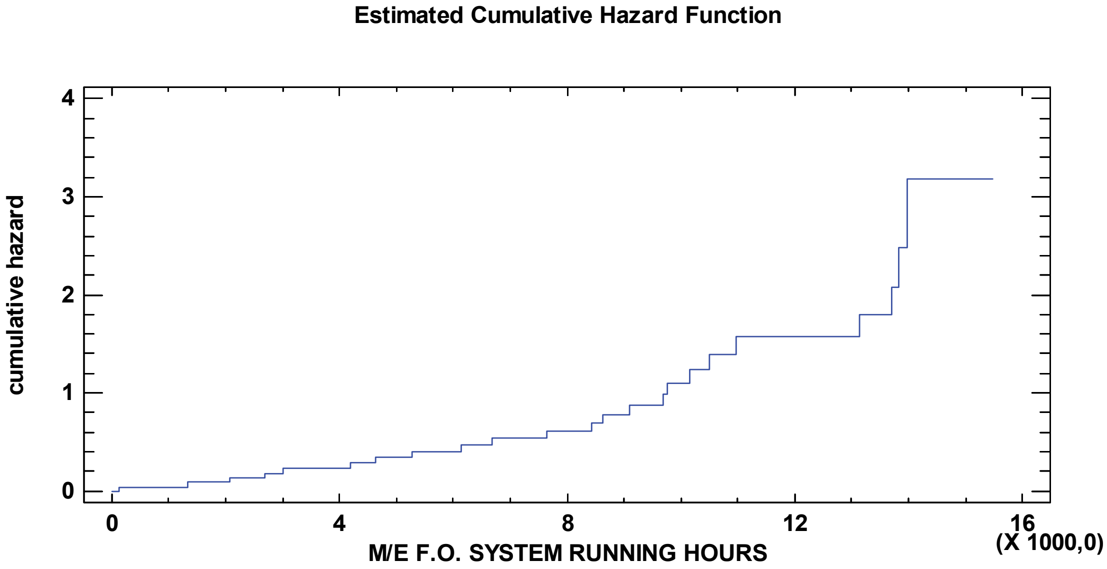

Figure 31: Cumulative hazard function plot of Main Engine's fuel oil system failures

The cumulative hazard function is not a probability and describes the accumulated risk up to time of a failure. The grater the value of the cumulative hazard the greater the risk for failure. From the plot (Figure 31) of the function it is observed a steady increasing of the risk until 8,500 hours. Between the 8,500 hours and 11,000 hours approximately and after 13,000 hours the hazard has increased growth rate.

Table 8: Product-Limit (Kaplan-Meier) Estimates

Time	*Status*	*Number at Risk*	*Cumulative Survival*	*Standard Error*	*Cumulative Hazard*
140	FAILED	23	0,9583	0,0408	0,0426
1341	FAILED	22	0,9167	0,0564	0,0870
2064	FAILED	21	0,8750	0,0675	0,1335
2692	FAILED	20	0,8333	0,0761	0,1823
3022	FAILED	19	0,7917	0,0829	0,2336
4199	FAILED	18	0,7500	0,0884	0,2877
4626	FAILED	17	0,7083	0,0928	0,3448
5270	FAILED	16	0,6667	0,0962	0,4055
6150	FAILED	15	0,6250	0,0988	0,4700
6684	FAILED	14	0,5833	0,1006	0,5390
7641	FAILED	13	0,5417	0,1017	0,6131
8435	FAILED	12	0,5000	0,1021	0,6931
8628	FAILED	11	0,4583	0,1017	0,7802
9097	FAILED	10	0,4167	0,1006	0,8755
9691	FAILED	9	0,3750	0,0988	0,9808
9750	FAILED	8	0,3333	0,0962	1,0986
10164	FAILED	7	0,2917	0,0928	1,2321
10490	FAILED	6	0,2500	0,0884	1,3863
10969	FAILED	5	0,2083	0,0829	1,5686
13140	FAILED	4	0,1667	0,0761	1,7918
13706	FAILED	3	0,1250	0,0675	2,0794
13820	FAILED	2	0,0833	0,0564	2,4849
13979	FAILED	1	0,0417	0,0408	3,1781
15479	FAILED	0	0,0000	0,0000	

Table 8 shows estimated survival probabilities based on the data. Each row of the table represents a single data value, displayed in increasing order. If the data value represents a failure or death, the status column indicates FAILED. The number at risk is the number of items which have survived up until each data value. For each unique failure time, the data displays the estimated survival probability, the standard error of that estimate, and the estimated hazard function.

For example at the 8,435 hours there are still 12 components that have survived and the survival probability for one component to survive until this time is 0.5 however the same component has a risk of failure past this time 0.6931 and increasing sharply for the next running hours.

This example can be done more understandable if one take under consideration the next table of estimated times at which given percentages of the item will be still operating.

Table 9: Estimated percentiles of Main Engine's fuel oil system failures lifetime distribution

Percentile	*Estimate*	*Standard Error*
95,0	1341,0	
90,0	2064,0	1378,2
80,0	3022,0	1274,3
70,0	5270,0	1501,8
60,0	6684,0	1908,8
50,0	8628,0	1472,5
40,0	9691,0	887,0
30,0	10164,0	711,4
20,0	13140,0	1957,2
10,0	13820,0	378,6

The percentiles estimate the length of time which a selected percentage of the items will survive. The first line shows that 95% of the items will survive for a length of time equal to 1,341 hours. The standard errors of the percentiles give an idea of how well these percentiles have been estimated given the available data, that's why when the running hours increasing and there are more data the standard error is less.

5.1.4 Parametric Analysis

Despite the fact that non parametric tests have the truly attractive property of making fewer assumption about the distribution which describes the under examination population of the sample along with smaller size of observations that are needed the result of a parametric analysis are more powerful (Richard Chin, 2008).

In other words, although non parametric methods are helpful much of the time and essential, the parametric ones conclude to safer results.

5.1.4.1 Test for Normality

Before all else must be checked if a theoretical normal distribution can be applied to describe the data.

The table 10 shows the results of several tests which ran to determine whether the data can be adequately modeled by a normal distribution.

The chi-square test divides the range of data into 14 equally probable classes and compares the number of observations in each class to the number expected.

The Shapiro-Wilk test is based upon comparing the quantiles of the fitted normal distribution to the quantiles of the data.

The standardized skewness test looks for lack of symmetry in the data. The standardized kurtosis test looks for distributional shape which is either flatter or more peaked than the normal distribution (Statgraphics, 2009).

Table 10: Results of tests for normality

Test	*Statistic*	*P-Value*
Chi-Square	8,66667	0,65263
Shapiro-Wilk W	0,966026	0,573828
Skewness Z-score	0,111033	0,911585
Kurtosis Z-score	-1,34559	0,178434

Since the smallest P-value amongst the tests of performed is greater than 0,05 (Table 10) the sample comes from a normal distribution with 95% confidence.

5.1.4.2 Comparison of Distributions

In order to decide which distribution fits to the data most properly the described goodness of fit tests are compared for several theoretical distributions.

Table 11: Comparison of Alternative Distributions

Distribution	*Est. Parameters*	*Chi-Square*	*Kolmogorov Smirnov*	*Anderson Darling*
Normal	2	0,830118	0,0874868	0,291754
Logistic	2	0,836435	0,0886597	0,247807
Smallest Extreme Value	2	0,409417	0,0958632	0,361703
Laplace	2	0,610512	0,130732	0,52889
Largest Extreme Value	2	0,817594	0,136704	0,427556
Weibull	2	0,896625	0,147304	0,560129
Loglogistic	2	0,0947534	0,160019	0,922304
Gamma	2	0,227125	0,168689	0,819236
Lognormal	2	0,0043647	0,179005	1,58829
Exponential	1	0,142077	0,204606	1,87385
Birnbaum-Saunders	2	0,000386197	0,333266	4,67264

Inverse Gaussian	2	0,000134988	0,351727	5,25797
Pareto	1	6,13953E-14	0,521606	8,97705

According to the Table 11 although the ideal distribution is the Normal, the Logistic distribution has very close values.

Below are presented the goodness of fit test for these two distributions.

Table 12: Results Chi-Square Test

	Normal	*Logistic*
Chi-Square	62,77563	2,82789
D.f.	6	6
P-Value	0,836435	0,830118

Table 13: Results of Kolmogorov-Smirnov Test

	Normal	*Logistic*
DPLUS	0,0822753	0,0778663
DMINUS	0,0874868	0,0886597
DN	0,0874868	0,0886597
P-Value	0,992916	0,99166

Table 14: Results of Anderson-Darling Test

	Normal	*Logistic*
A^2	0,291754	0,247807
Modified Form	0,291754	0,247807
P-Value	>=0.10	>=0.10

The chi-square test divides the range of data into non overlapping intervals and compares the number of observations in each class to the number expected based on the fitted distribution. The Kolmogorov-Smirnov test computes the maximum distance between the cumulative distribution and the cdf of the fitted distribution. The Anderson Darling test compares the empirical distribution function to the fitted cdf in different ways.

The P-value of all three tests presented in the above tables indicates that the Normal fits the data better than the Logistic distribution.

Another way to decide is to plot the two distributions together with the life time data to compare which one approaches them better. In the next quantile-quantile plot (Figure 32), which shows the fraction of observations plotted versus the equivalent percentiles of the fitted distributions (Adam loy, 2014), is very difficult one to make safe conclusions.

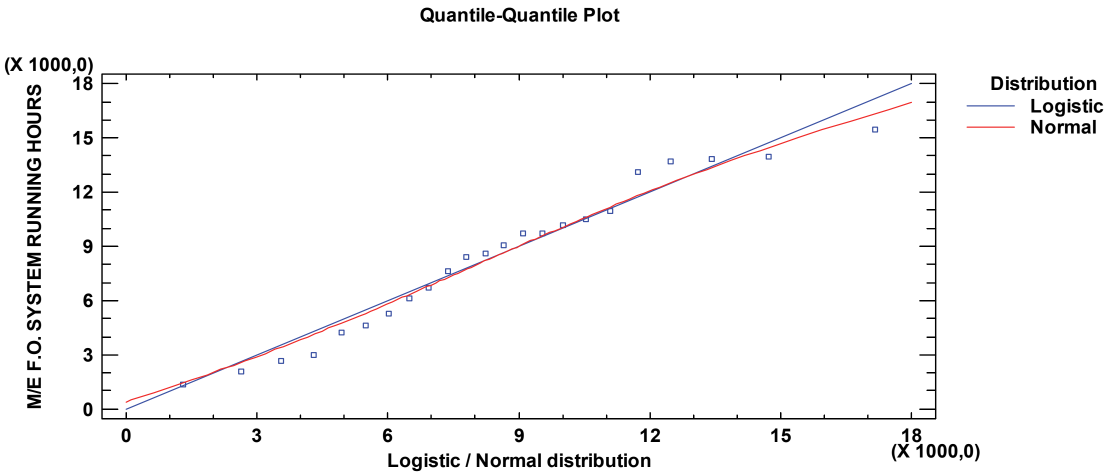

Figure 32: Quantile-Quantile plot of Logistic and Normal distribution

The significant values that describe the normal distribution are the mean value μ and the standard deviation σ. For our data these values are:

- $\mu = 7965{,}71$
- $\sigma = 4397{,}6$

5.1.4.3 Reliability Concept –Fitting of Normal Distribution

Since the theoretical distribution that describes the population of the failure data is established safe conclusion regarding the reliability, failure and survival rate can be produced.

The plot of the basic functions of the Normal distribution along with the calculation of the tabulation values regarding the probabilities of survival, failure etc. give the opportunity to understand deeply the fuel oil system of the main engine.

5.1.4.4 Cumulative Distribution Plot

The integral of the density function is the cumulative probability and gives the increasing probability of components failing at time t.

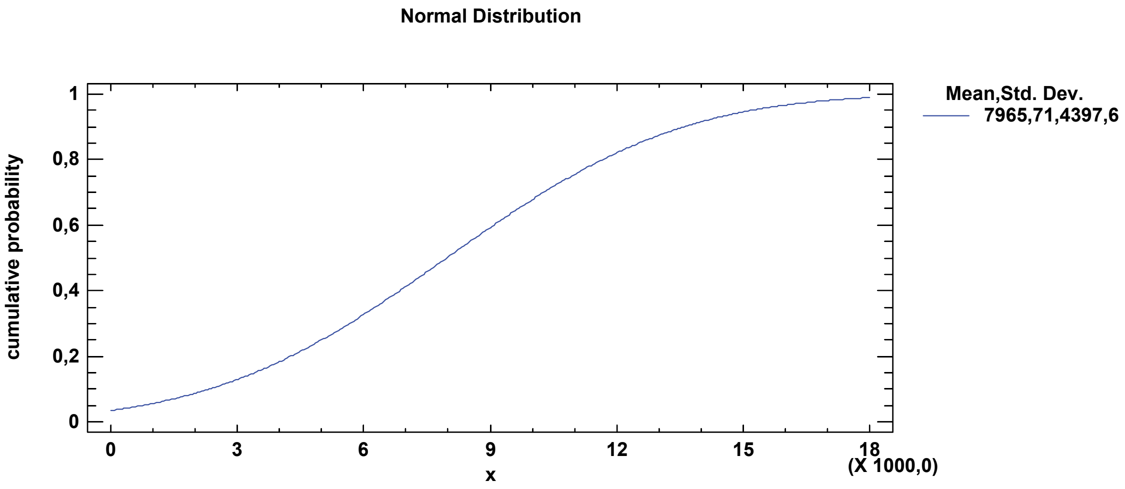

Figure 33: Cumulative distribution function plot of Normal distribution

Using the cumulative distribution the answer for example which is the probability a component to work for less than 8000 hours can be given from the plot (Figure 33), the vertical line at 8,000 hours shows that the probability is 0.503.

The Table 15 gives all the probabilities from 1,000 up to 18,000 hours.

Table 15: Cumulative failure probabilities

Time	*Cumulative Probability*
1000	0,0565989
2000	0,0874566
3000	0,129409
4000	0,183583
5000	0,25003
6000	0,327437
7000	0,413089
8000	0,503114
9000	0,592973

Time	*Cumulative Probability*
10000	0,678173
11000	0,7549
12000	0,82053
13000	0,873851
14000	0,914996
15000	0,945154
16000	0,966148
17000	0,98003
18000	0,988748

Another interesting statistical element that can be extracted if one inverses the cumulative distribution function and converts the probability to percent as presented below.

Table 16: Critical hours of Normal Distribution

Percent %	*Critical Hours*
10	2329
20	4264
30	5659
40	6851
50	7965
60	9079
70	10271
80	11666
90	13601
99	18196

The critical hours are defined as the largest value for the Normal such that the probability of not exceeding that value does not exceed the area specified. For example, the output indicates that 9,079 is the largest value such that the percent of the sample not exceeding 9,079 is less than or equal to 60%.

5.1.4.5 Survival Plot

The survival function is given as S(t) = 1- F(t) where F(t) is the cdf. Practically is the opposite of the cdf and gives the probability an individual of the sample can survive at least for a time t.

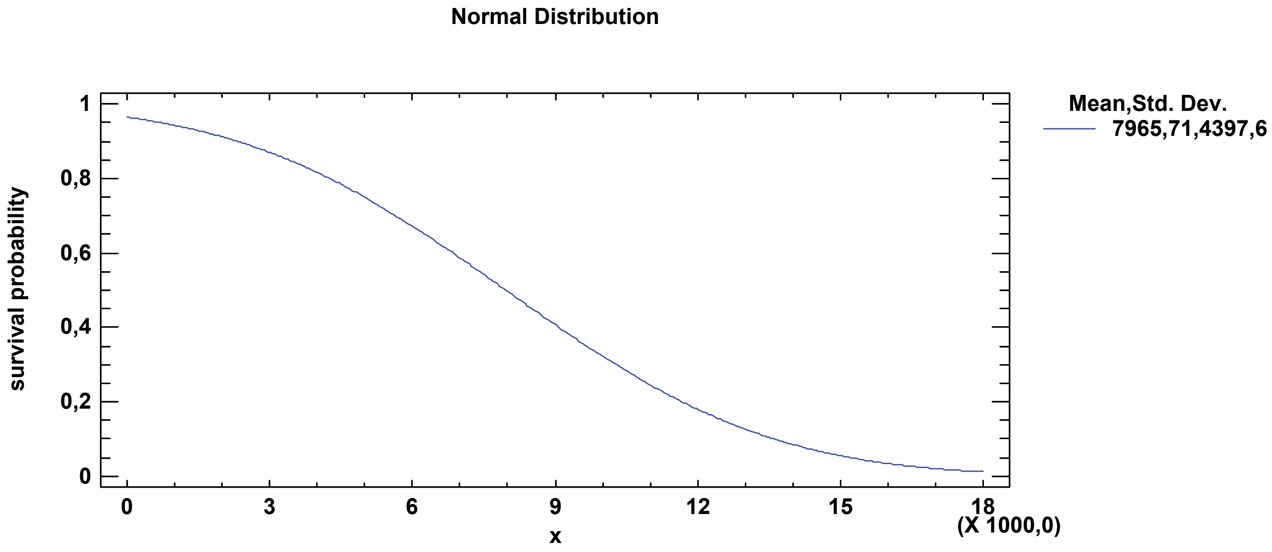

Figure 34: Survival function plot of Normal distribution

The following table gives all the probabilities from 1,000 up to 18,000 hours.

Table 17: Cumulative survival probabilities

Time	*Survival Probability*
1000	0,943401
2000	0,912543
3000	0,870591
4000	0,816417
5000	0,74997
6000	0,672563
7000	0,586911
8000	0,496886
9000	0,407027
10000	0,321827
11000	0,2451
12000	0,17947
13000	0,126149
14000	0,0850037
15000	0,0548463
16000	0,0338519
17000	0,0199699
18000	0,0112515

Taking under consideration the Figure 34 and table 17 one can understand the possibility of a component to survive after curtain running hours for example a component has a probability of 0.321827 to be operational after 10,000 hours.

5.1.4.6 Hazard Plot

The hazard function or risk function or failure rate is not a probability as has already been mentioned and can have values greater than 1.

Is the condition probability that a death of a component will occur in the interval (t, t+dt) given that has not occurred yet.

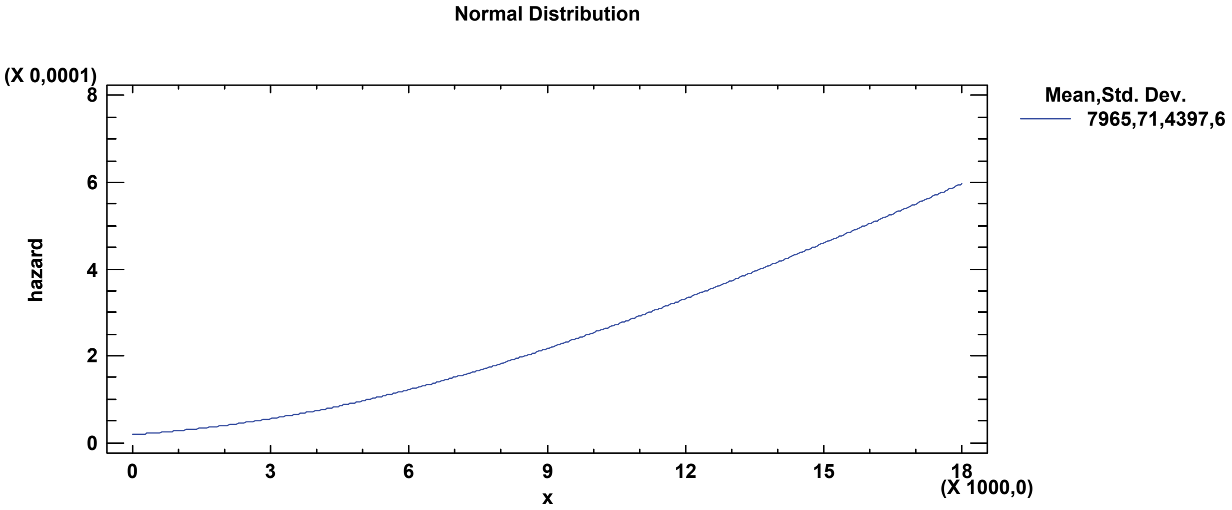

Figure 35: Survival function plot of Normal distribution

The plot of hazard function indicates a steadily increasing rate along the passing of time. From this hazard rate one can assume that the main factor of failure is the collapse of the components from the wear of the time (Nelson, 1982).

5.2 Auxiliary Engine Fuel Oil System Failures

In this chapter the very same procedure was followed in order to evaluate the data that concern failures to auxiliary engine's fuel oil system. The running hours till failure are listed below in Table 18.

Table 18: Running hours of Auxiliary Engine's fuel oil system failures

21800	27147
21250	7885
7606	17503
10625	9398
19150	18796
10458	18132
22333	20756
8761	18927
10455	21658
19049	21978

5.2.1 Box Plot diagram and Outlier points

A box plot diagram is used to identify possible outliers of the population.

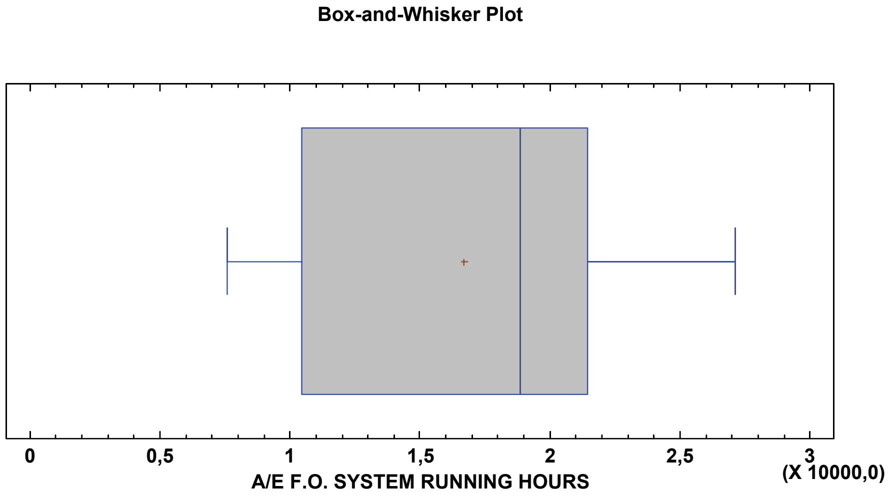

Figure 36: Box plot diagram of Auxiliary Engine's fuel oil system failures

Since the graph (Figure 36) does not indicate any outlier points all the failure data will be used in the analysis. Another observation that can be extracted from the graph is that the median is close to the 75th quartile and the upper whisker is longer meaning that the running hours since failure of the data are skewed to higher levels (Potter, 2006).

The next table summarizes the basic statistic measures of the box plot.

Table 19: Running hours of Auxiliary Engine's fuel oil system failures

Count	20
Average	16683,3
Median	18861,5
Standard deviation	5945,61
Minimum	7606,0
Maximum	27147,0
Range	19541,0
Lower quartile	10456,5
Upper quartile	21454,0
Interquartile range	10997,5

The maximum and the minimum values of the data are 7606 and 27,147 hours respectively, the median (Q2) is 18,861.5, the 25th percentile (Q1) is 10,456.5 and the 75th percentile (Q3) is 21454. Also the interquartile range (IQR) of the sample is 10,997.5.

5.2.2 Histogram

The sequence of hours till failure can be seen through the next histogram.

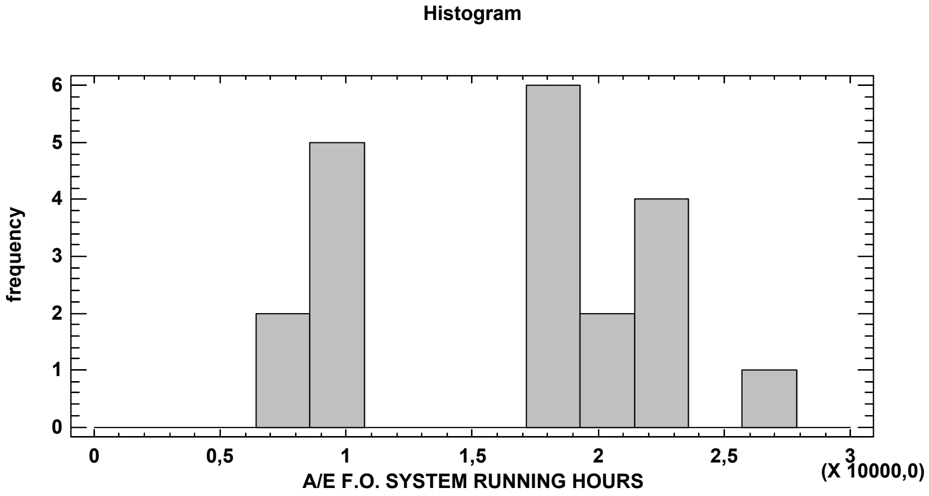

Figure 37: Histogram of Auxiliary Engine's fuel oil system failures

The frequency distribution of the data seems not to follow a specific symmetry (Figure 37), however a slightly cluster to the right can be considered. Also around 18000 hours there is a significant concentration of failures.

The board below (Table 20) contains the class interval and the frequencies of each one. Despite the fact that the data were divided to 14 classes the six of them have frequencies.

Table 20: Frequency tabulation table of Auxiliary Engine's fuel oil system failures

Class	*Lower Limit*	*Upper Limit*	*Midpoint*	*Frequency*	*Relative Frequency*	*Cumulative Frequency*	*Cum. Rel. Frequency*
1	0	2142,86	1071,43	0	0,0000	0	0,0000
2	2142,86	4285,71	3214,29	0	0,0000	0	0,0000
3	4285,71	6428,57	5357,14	0	0,0000	0	0,0000
4	6428,57	8571,43	7500,0	2	0,1000	2	0,1000
5	8571,43	10714,3	9642,86	5	0,2500	7	0,3500
6	10714,3	12857,1	11785,7	0	0,0000	7	0,3500

7	12857,1	15000,0	13928,6	0	0,0000	7	0,3500
8	15000,0	17142,9	16071,4	0	0,0000	7	0,3500
9	17142,9	19285,7	18214,3	6	0,3000	13	0,6500
10	19285,7	21428,6	20357,1	2	0,1000	15	0,7500
11	21428,6	23571,4	22500,0	4	0,2000	19	0,9500
12	23571,4	25714,3	24642,9	0	0,0000	19	0,9500
13	25714,3	27857,1	26785,7	1	0,0500	20	1,0000
14	27857,1	30000,0	28928,6	0	0,0000	20	1,0000

5.2.3 Non Parametric Analysis

In this section non parametric methods will be used to estimate the failure and the survival probabilities as well as the hazard rate of the data without implementing any specific distribution.

5.2.3.1 Non Parametric Estimates

To continue with the non parametric analysis of the auxiliary engine’s fuel oil system failures the main factors of the data must be presented. The table below indicates the significant estimations for the collected failures.

Table 21: Descriptive non parametric estimates of Auxiliary Engine’s fuel oil system failures

Count	20
Mean	16683,3
Median	18861,5
Standard deviation	5945,61
Stnd. skewness	-0,54
Stnd. kurtosis	-1,13
Coeff. of variation	35,638%

5.2.3.2 Empirical Cumulative Distribution

A primary way to describe the data as have already been mentioned is through the empirical cumulative distribution.

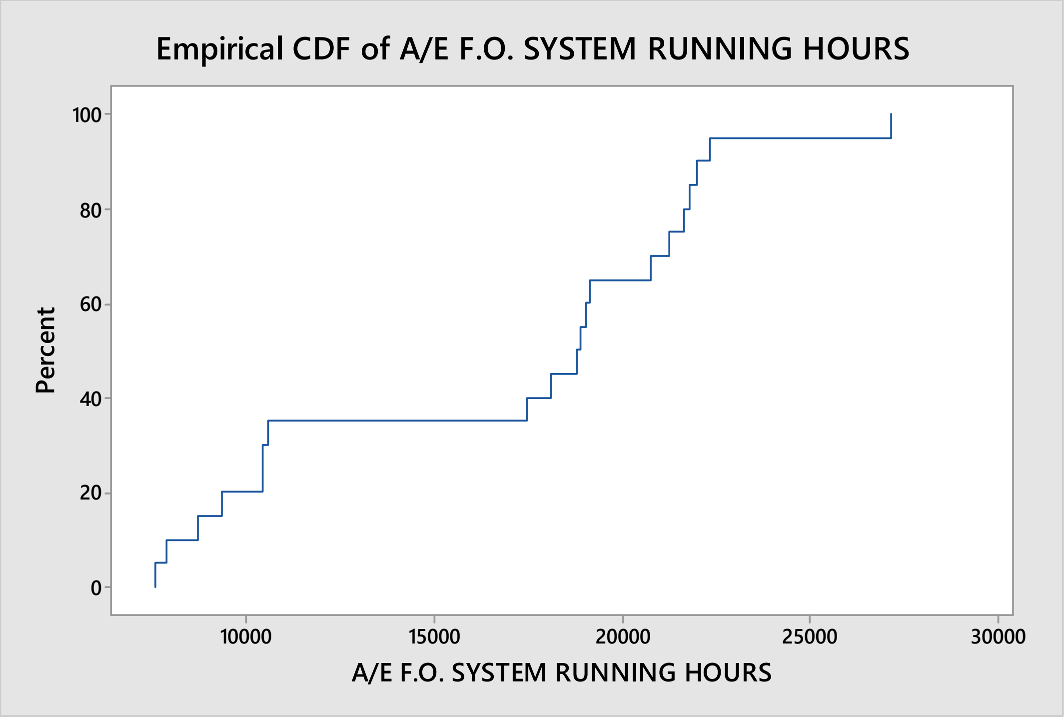

Figure 38: Empirical cumulative distribution function plot of Auxiliary Engine's fuel oil system failures

From the Figure 38 is observed that 50% of the fuel oil system parts will have failed since the 18,900 running hours.

5.2.3.3 Cumulative Failure Distribution

The cumulative probabilities of the system from the beginning of their operation till their death are provided from the cumulative distribution plot.

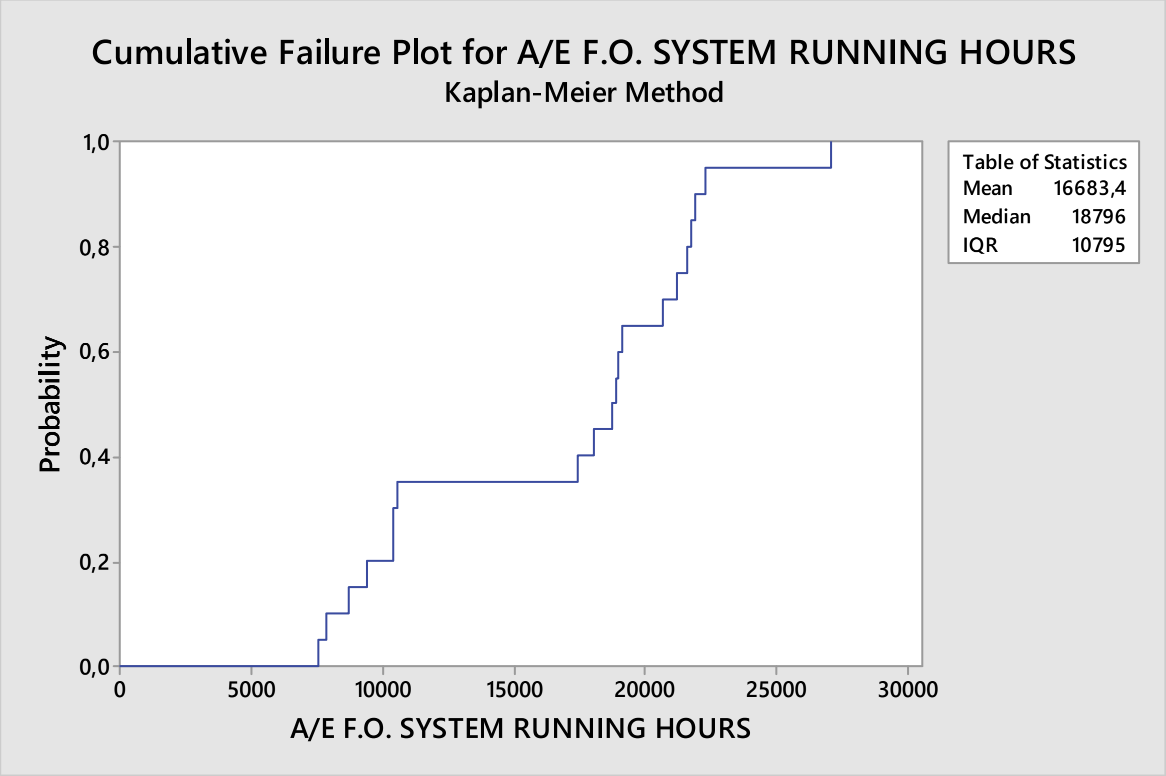

Figure 39: Cumulative distribution function plot of Auxiliary Engine's fuel oil system failures

The probabilities of the plot can be seen in the following table. Till 7,500 hours the system does not display any failures. The probabilities increasing with a step of 0,05 and in agreement with the empirical distribution function that at 18,796 hours the probability that a component will fail is 0,5.

Table 22: Cumulative failure probabilities and standard errors of Main Engine's fuel oil system failures

Time	*Cumulative Failure*	*Standard Error*
7606	0,05	0,05
7885	0,10	0,07
8761	0,15	0,08
9398	0,20	0,09
10455	0,25	0,10
10458	0,30	0,10
10625	0,35	0,11
17503	0,40	0,11
18132	0,45	0,11
18796	0,50	0,11

18927	0,55	0,11
19049	0,60	0,11
19150	0,65	0,11
20756	0,70	0,10
21250	0,75	0,10
21658	0,80	0,09
21800	0,85	0,08
21978	0,90	0,07
22333	0,95	0,05
27147	1,00	0,00

5.2.3.4 Survival Distribution and Cumulative Hazard Plot

For the better understanding of the system's reliability, the knowing of the survival probabilities is a necessity. The survival plot is the opposite of the cumulative distribution and gives the probability a component to survive passing a time t.

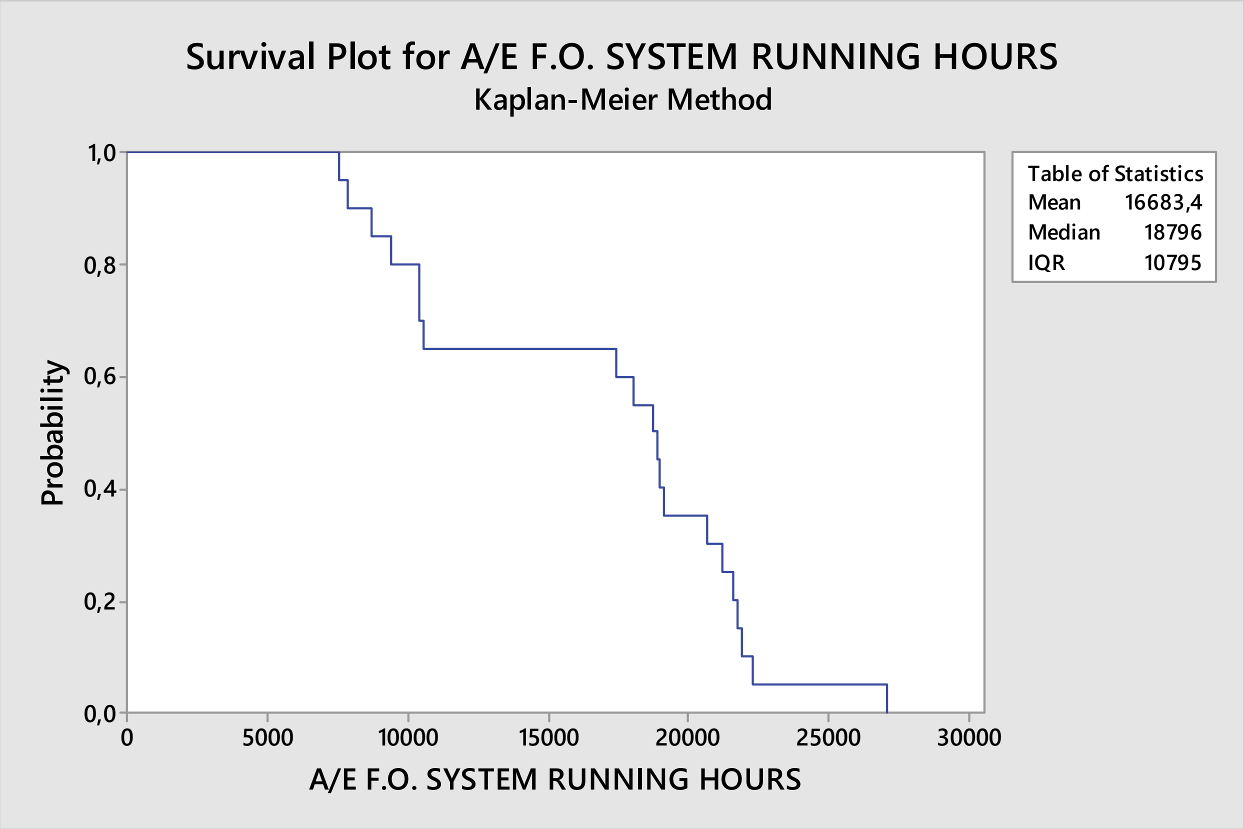

Figure 40: Survival function plot of Auxiliary Engine's fuel oil system failures

As the Figure 40 indicates after 16,000 hours the probability not to have a failure in the system decreasing rapidly, until this point the probability of a component to survive is approximately 0,65. A same pattern is observed also between 6,000 and 10,000 hours. In addition according to the graph all the components will survive till 7,500 hours.

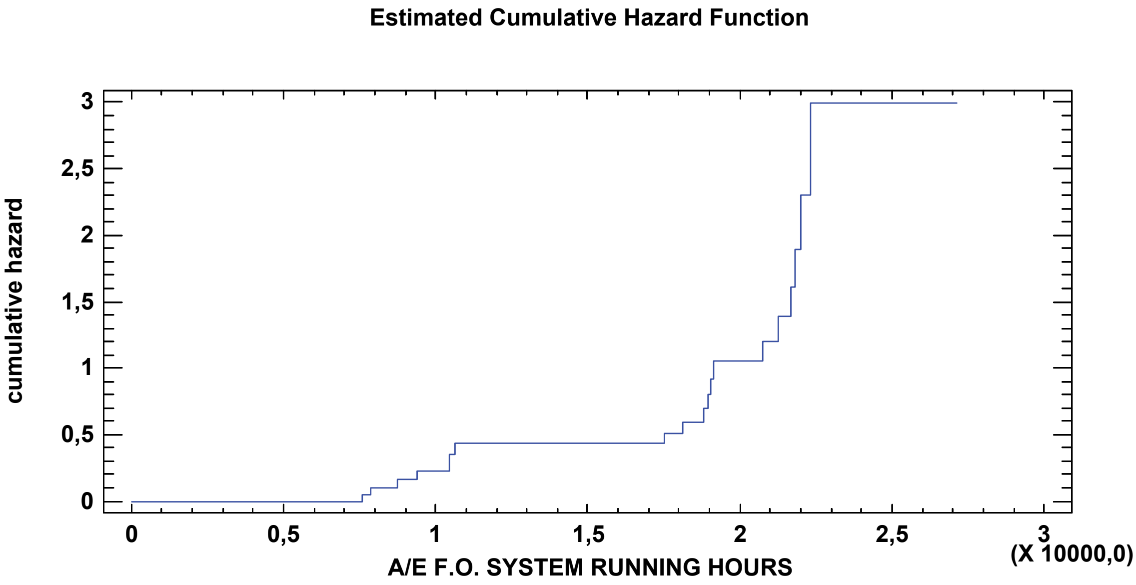

Figure 41: Cumulative hazard function plot of Auxiliary Engine's fuel oil system failures

The cumulative hazard function is not a probability and describes the risk rate through time. The Figure 41 shows that the risk of a failure increases with a low rate between 7,500 and 11,000 hours and then remains steady for 7,000 hours more. However from the 18,000 hours the hazard rate is increasing rapidly, after this point there is a high risk which always increasing an individual that had survived upon this time to fail in the next hours.

Table 22: Product-Limit (Kaplan-Meier) Estimates

Time	*Status*	*Number at Risk*	*Cumulative Survival*	*Standard Error*	*Cumulative Hazard*
7606,0	FAILED	19	0,9500	0,0487	0,0513
7885,0	FAILED	18	0,9000	0,0671	0,1054
8761,0	FAILED	17	0,8500	0,0798	0,1625

9398,0	FAILED	16	0,8000	0,0894	0,2231
10455,0	FAILED	15	0,7500	0,0968	0,2877
10458,0	FAILED	14	0,7000	0,1025	0,3567
10625,0	FAILED	13	0,6500	0,1067	0,4308
17503,0	FAILED	12	0,6000	0,1095	0,5108
18132,0	FAILED	11	0,5500	0,1112	0,5978
18796,0	FAILED	10	0,5000	0,1118	0,6931
18927,0	FAILED	9	0,4500	0,1112	0,7985
19049,0	FAILED	8	0,4000	0,1095	0,9163
19150,0	FAILED	7	0,3500	0,1067	1,0498
20756,0	FAILED	6	0,3000	0,1025	1,2040
21250,0	FAILED	5	0,2500	0,0968	1,3863
21658,0	FAILED	4	0,2000	0,0894	1,6094
21800,0	FAILED	3	0,1500	0,0798	1,8971
21978,0	FAILED	2	0,1000	0,0671	2,3026
22333,0	FAILED	1	0,0500	0,0487	2,9957

The Table 22 summarizes the estimated survival probabilities based on the data. The values of the hours are placed in increasing order and the status “FAILED” states that the individual has stopped to operate at this time. The number at risk is the number of items which have survived up until each data value. For each unique failure time, the data displays the estimated survival probability, the standard error of that estimate, and the estimated hazard function.

Combining these results along with the cumulative failure probabilities the conclusion that can be made is that after 17,500 hours the possibility to have a failure is growing.

Table 23: Estimated percentiles of Main Engine’s fuel oil system failures lifetime distribution

Percentile	*Estimate*	*Standard Error*
95,0	7606,0	
90,0	7885,0	
80,0	9398,0	1532,4
70,0	10458,0	838,2
60,0	17503,0	5604,3
50,0	18796,0	1061,3
40,0	19049,0	258,5
30,0	20756,0	1503,5
20,0	21658,0	622,5
10,0	21978,0	301,8

In Table 23 the percentiles estimate to which time of the observations a selected percentage of the items will survive. Making visible that since the 17,503 hours the 60% of the population will survive. After that point the interval between the running hours, while the percentile decrease, is smaller than previously. For example from the 70th to the 60th percentile there is a difference of 7,045 hours in comparison with the 70th and the 60th percentile which the difference is 1,293 hours. Also the used program could not calculate the standard error for the 95% and 90% percentile.

5.2.4 Parametric Analysis

As mentioned before the parametric analysis can give a better knowledge of the examined data and make feasible to produce results and conclusion regarding the population that came from.

5.2.4.1 Test for Normality

Each test examines the null hypothesis in order to verify if the population of the observations can be described by a normal distribution.

Table 24: Results of test for normality

Test	*Statistic*	*P-Value*
Chi-Square	8,66667	0,65263
Shapiro-Wilk W	0,96603	0,57383
Skewness Z-score	0,11103	0,91159
Kurtosis Z-score	-1,34559	0,17843

Since the smallest P-value amongst the tests performed (Table 24) is greater than 0,05 the sample comes from a normal distribution with 95% confidence.

5.2.4.2 Comparison of Distributions

The decision of the distribution that will be applied to the data is crucial, because if is not the correct one is going to lead to wrong assumptions.

For that reason the described goodness of fit tests are used and their outcome is compared for several theoretical distributions in Table 25.

Table 25: Comparison of Alternative Distributions

Distribution	*Est. Parameters*	*Chi-Square*	*Kolmogorov Smirnov*	*Anderson Darling*
Smallest Extreme Value	2	0,0151613	0,195526	0,781301
Uniform	2	0,00134285	0,196354	
Normal	2	0,0261443	0,204826	1,07776
Weibull	2	0,00432299	0,208903	1,18285
Logistic	2	0,00247512	0,212101	1,10323
Loglogistic	2	0,000847331	0,228461	1,42213
Gamma	2	0,00791471	0,250181	1,3749
Largest Extreme Value	2	0,0470551	0,25564	1,36485
Laplace	2	0,00247512	0,262633	1,68244
Lognormal	2	0,00791471	0,265755	1,42752
Birnbaum-Saunders	2	0,0151613	0,273168	1,49842
Inverse Gaussian	2	0,0151613	0,27481	1,51753
Exponential	1	4,34426E-7	0,366125	3,99312

It is observed that the Smallest Extreme Value, the Uniform and the Normal distribution are the most suitable for the data. However since the Uniform in not considered optimum to describe life data is rejected.

For safer conclusion will see each test separately for the other two distributions.

Table 26: Results Chi-Square Test

	Normal	*Smallest Extreme Value*
Chi-Square	9,25	10,4417
D.f.	3	3
P-Value	0,0261443	0,0151613

Table 27: Results of Kolmogorov-Smirnov Test

	Normal	*Smallest Extreme Value*
DPLUS	0,19589	0,195526
DMINUS	0,204826	0,139284
DN	0,204826	0,195526
P-Value	0,374653	0,435612

Table 28: Results of Anderson-Darling Test

	Normal	*Smallest Extreme Value*
A^2	1,07776	0,781301
Modified Form	1,07776	0,781301
P-Value	>=0.10	>=0.10

The chi-square test (Table 26) gives a bigger P-value of the Normal distribution in comparison with the Smallest Extreme Value and the Kolmogorov-Smirnov test (Table 27) the opposite. In the Anderson-Darling test (Table 28) is indicated that both distribution have P-value over 0,1.

In order to choose the best distribution the quantile-quantile plot and the eyeball test. In other words the following graph will show which one approach the observations better.

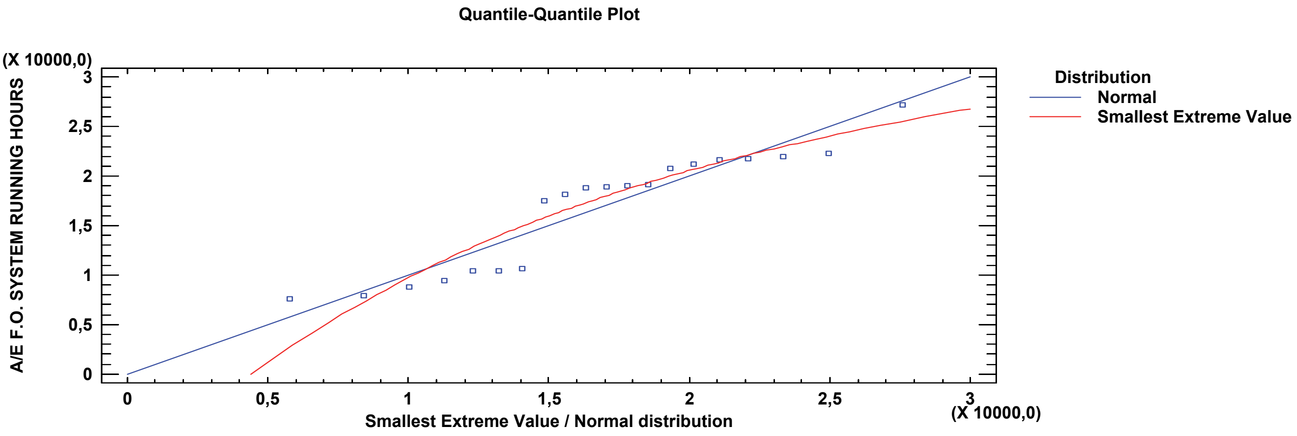

Figure 42: Quantile-Quantile plot of Logistic and Normal distribution

Observing the quantile-quantile plot (Figure 42) one can conclude that the Smallest Extreme Value distribution fits adequately to the data.

5.2.4.3 Reliability Concept –Fitting of Smallest Extreme Distribution

The Smallest Extreme Value distribution is also known as log-Weibull distribution. Is a member of a broader category known as Extreme Value Distributions where the Weibull also belongs. More specifically this category is consisted by three types (Type I, Type II, Type III) which are commonly used to represent the maximum or minimum of a number of samples of various distributions. The Smallest Extreme

Value is included in Type I which called Gumbel distribution (Chang, 2015). This distribution is often used for modeling the life of components that experience very quick wear out after reaching a certain age ("Life Data Analysis Reference," 2015).

- The probability density function: $f(t) = 1/\sigma e^{(t-\frac{\mu}{\sigma})} e^{-e^{(t-\frac{\mu}{\sigma})}}, \quad t > 0$

Where the parameter μ is called location parameter and the parameter σ scale parameter and are both positive.

- The probability cumulative function: $F(t) = 1 - e^{-e^{t}}, \quad t > 0$

The significant values in order to describe the Smallest Extreme Distribution for the observed data are:

- $\mu = 19474$
- $\sigma = 4957{,}39$

After the establishment of the theoretical distribution that describes adequately the failure data the analysis of the reliability can proceed extracting tabulation results and plots for the population.

5.2.4.4 Probability Density Plot

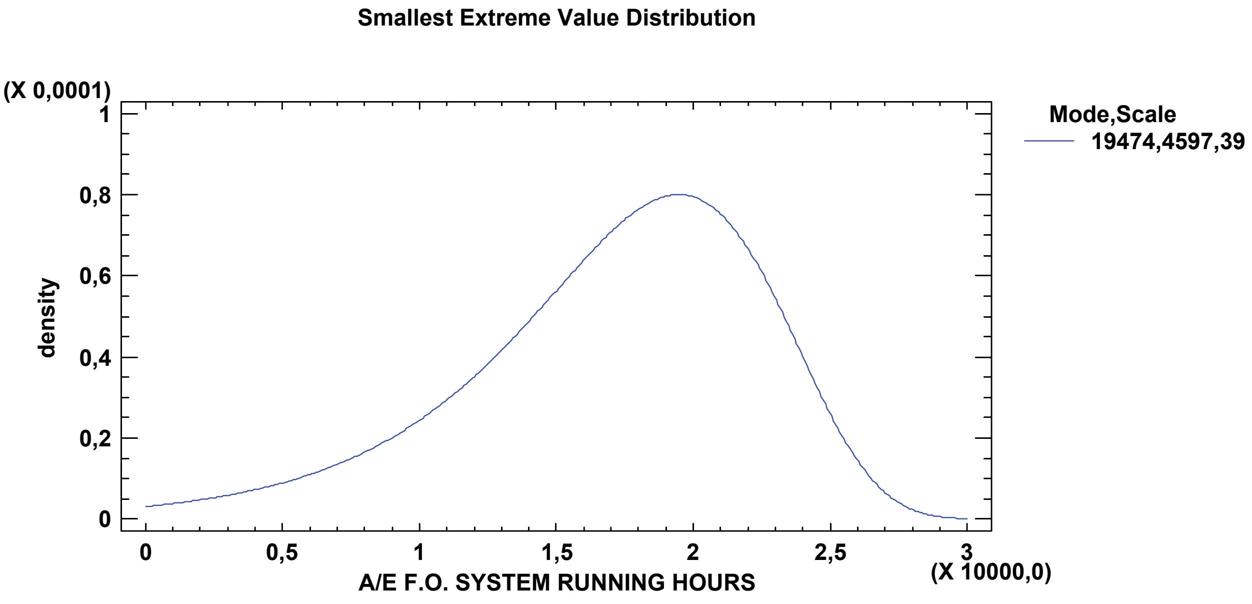

Figure 43: Probability density function plot of Smallest Extreme Value distribution

The probability density plot (Figure 43) of the distribution shows a concentration of the failure to the right, around to 20,000 hours.

5.2.4.5 Cumulative Distribution Plot

The cumulative probability function is given as:

$$F(t) = 1 - e^{-e^{t}}, \quad t > 0$$

and describes the increasing probability of a failure to occur until a specified time.

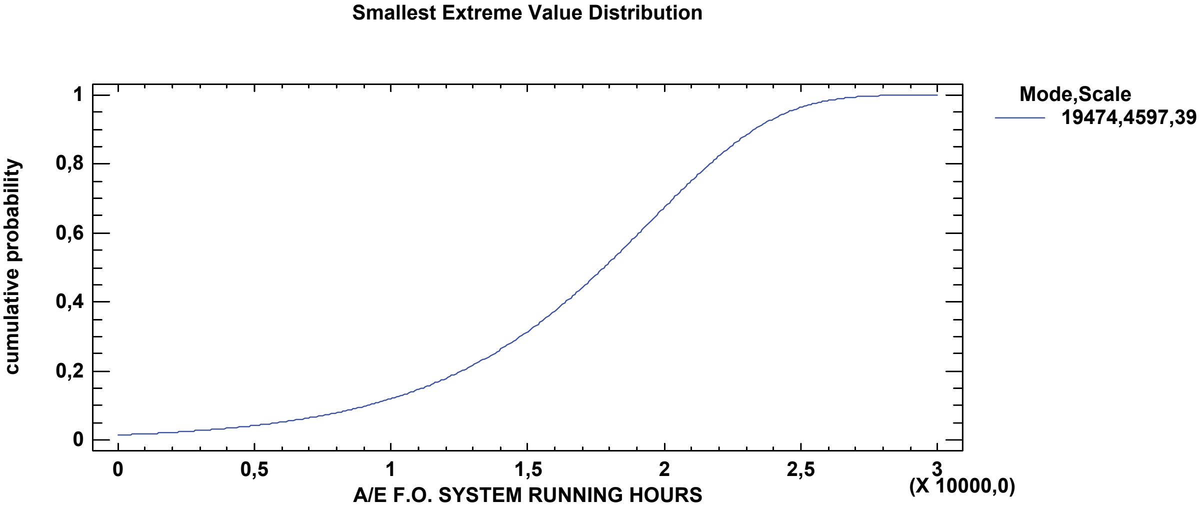

Figure 44: Cumulative distribution function plot of Smallest Extreme Value distribution

Figure 44 illustrates a smooth incensement until 14,000 hours and at this point till the 23,000 hours the curvature changes and an rapid upward inclination is observed.

The following table gives all the probabilities from 1,000 up to 30,000 hours.

Table 29: Cumulative failure probabilities

Time	*Cumulative Probability*	*Time*	*Cumulative Probability*
1000	0,0178216	16000	0,374815
2000	0,0221038	17000	0,442247
3000	0,0274004	18000	0,516015

4000	0,0339441
5000	0,0420165
6000	0,0519563
7000	0,0641677
8000	0,0791273
9000	0,0973889
10000	0,119584
11000	0,146412
12000	0,178623
13000	0,216971
14000	0,262151
15000	0,314692
19000	0,594257
20000	0,674116
21000	0,751833
22000	0,82312
23000	0,883888
24000	0,931189
25000	0,964089
26000	0,983998
27000	0,994141
28000	0,99832
29000	0,999644
30000	0,999948

From the Table 29 is pointed out that the probability to have a failure at the first 14,000 hours is only 0,26 however in the next 4,000 hours i.e. in 18,000 total running hours this probability reaches the 0,52 which is the double value.

Inverting the cumulative distribution the next table can be extracted.

Table 30: Critical hours of Normal Distribution

Percent %	*Critical Hours*
10	9128
20	12578
30	14734
40	16385
50	17788
60	19072
70	20327
80	21661
90	23308
99	26495

The largest value that the 50% of the population or less can operate without a failure is 17,788 hours (Table 30).

5.2.4.6 Survival Plot

The survival function is given as:

$$S(t) = e^{-e^{t}}, \quad t > 0$$

And gives the probability an individual of the sample can survive at least for a time t.

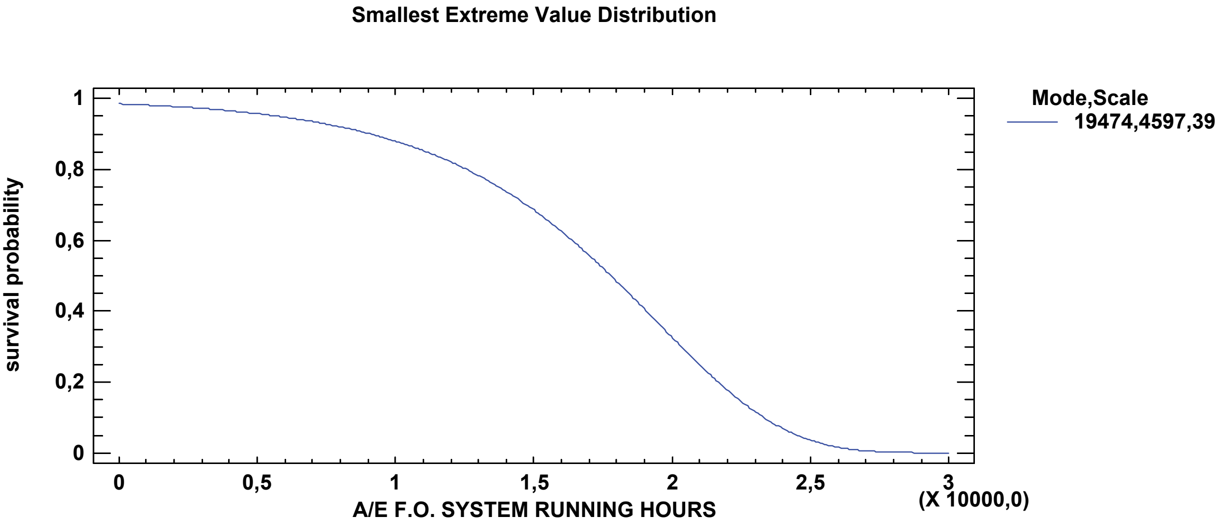

Figure 45: Survival function plot of Smallest Extreme Value distribution

The following table gives all the probabilities from 1,000 up to 30,000 hours.

Table 31: Cumulative survival probabilities

Time	*Survival Probability*		*Time*	*Survival Probability*
1000	0,982178		16000	0,625185
2000	0,977896		17000	0,557753
3000	0,9726		18000	0,483985
4000	0,966056		19000	0,405743
5000	0,957984		20000	0,325884
6000	0,948044		21000	0,248167
7000	0,935832		22000	0,17688

8000	0,920873
9000	0,902611
10000	0,880416
11000	0,853588
12000	0,821377
13000	0,783029
14000	0,737849
15000	0,685308

23000	0,116112
24000	0,0688106
25000	0,0359108
26000	0,0160018
27000	0,00585881
28000	0,00168044
29000	0,000355833
30000	0,00005167

Taking under consideration the Figure 45 and the Table 31 is observed, as expected from the previous analysis, that the probability of an individual to survive for the first 14000 operational hours is very large, more specifically is approximately 0,74. However this probability decreases along time rapidly from that point further.

5.2.4.7 Hazard Plot

The hazard function or risk function is not a probability, can have values greater than 1 and indicates the failure rate of a component in the interval (t, t+dt) given that has not yet failed.

The hazard function is:

$$H(t) = e^{\frac{t-\mu}{\sigma}}, \quad t > 0$$

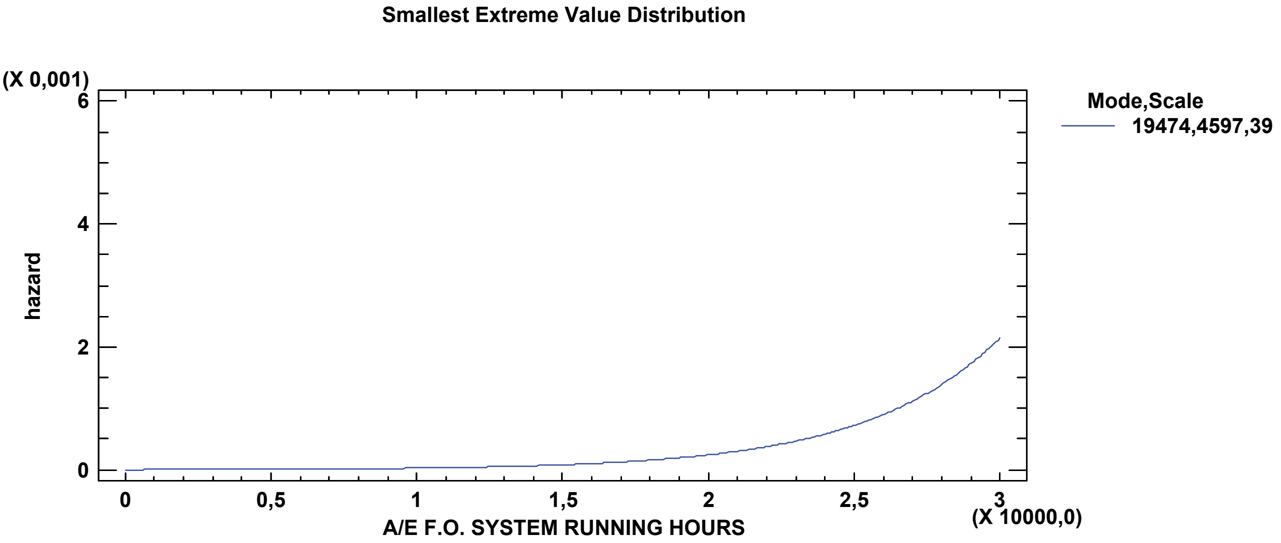

Figure 46: Hazard function plot of Smallest Extreme Value distribution

The plot of hazard function (Figure 46) is steady and increases after 17,500 hours. From this hazard rate one can assume that the components tend to fail after this point, meaning that the failures are a result of increased time of service

6 CONCLUSIONS

The purpose of this study is to assess the reliability of the most prone to malfunctions equipment on a vessel. In this thesis, so far, a statistical analysis has been addressed of real life data which concern failures of a fleet of tankers for the time period of two years. These failures initially categorized, mainly, regarding the spatial arrangement of a vessel and then each category divided to subcategories according to the schedule maintenance system of the company, that the data acquired, and the significance of the failures. As a result the main and the auxiliary engines seem to present the most malfunctions, especially the fuel oil system of these machineries is responsible for most of them.

The implementation of parametric and non parametric reliability methods to the operating hours till death field data regarding the systems of the main engine's and auxiliary engine's fuel oil system displayed increasing failure rate depending on time. Especially for the main engine, which follows the normal Gaussian distribution, the sharp increasement of the hazard rate reveals that the components of the system have high probabilities for failure as long as the operating hours heighten, showing sensitivity in the wear as this type of hazard rate depicts. From the other hand the auxiliary engines display another type of failure model, since the most failures are presented in the system after a certain point of operating hours and the hazard rate is steady increasing along their life time, meaning that the main reason of failure is the fulfillment of their operation.

Observing the results of the reliability analysis arises the need, initially, for improvements to the inspection and maintenance strategy. The reconnaissance of the problem and its fixing before converts to a failure is a necessary preventive action first and foremost for the already installed vessel's equipment. Based on this or similar researches more flexible and suitable maintenance schedules can be developed, centered around the reliability of each equipment. However, beforehand of such analyses is crucial to take under consideration the potential costs and dangers before make any decisions. Another aspect of knowing the equipment's rate of failure is given the opportunity for a better organized spare parts plan saving costs for the companies and decreasing the machineries unavailability. Also taking under consideration that the spare parts is one of the biggest fixed costs of a vessel's budget the reliability models can be used as a form of a more accurate annual financial prediction.

Even though the period of two years and the numbers of the vessels and failures was sufficient to draw conclusions in this analysis, is becoming understandable that more analytical calculations could be performed, leading to more solid outcomes, if the amount of data was larger. In addition if more information regarding the failures were available further research could be conducted regarding the criticality, the consequences and the cost.

Summarizing this thesis and observing the conclusions becomes apparent that further studies in the future should concentrate in the improvement of the maintenance and the spare parts plan based on the reliability models of similar to this thesis analyses. In addition more reliability data collection projects like OREDA and SRIC should be conducted and the participation of more and more shipping companies is essential. Another aspect for future research is the study of the consequences both to the human and the seaworthiness of the vessel as well as the costs of the failures. Last but not least is considered of great importance the researchers to analyze the factors that contribute to failures and optimize them.

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APPENDIX A

a) Graphs for the entire fleet

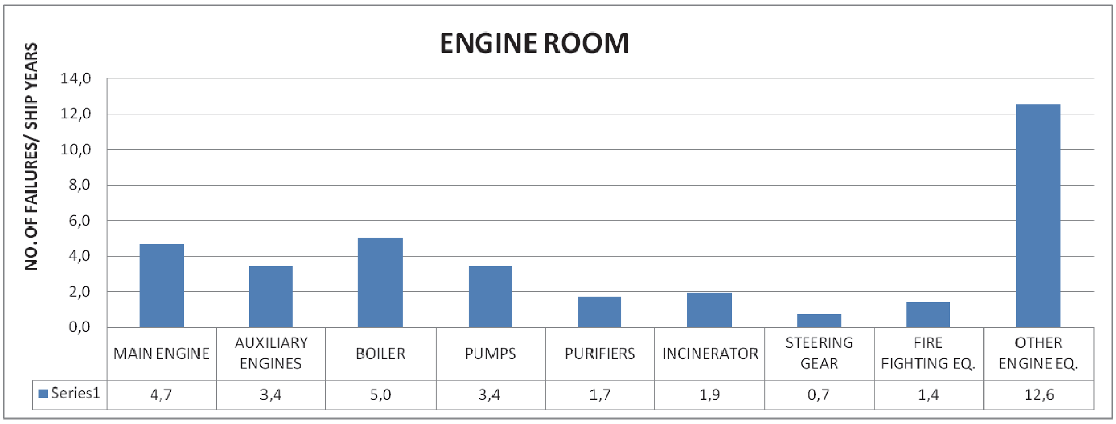

Figure 47: Number of failures divided by the ship years regarding each category of the Engine Room for the entire fleet

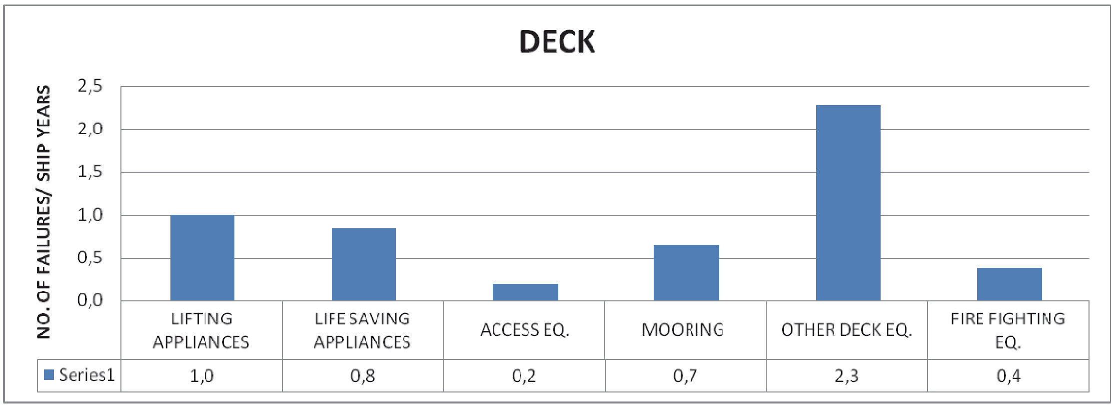

Figure 48: Number of failures divided by the ship years regarding each category of the Deck for the entire fleet

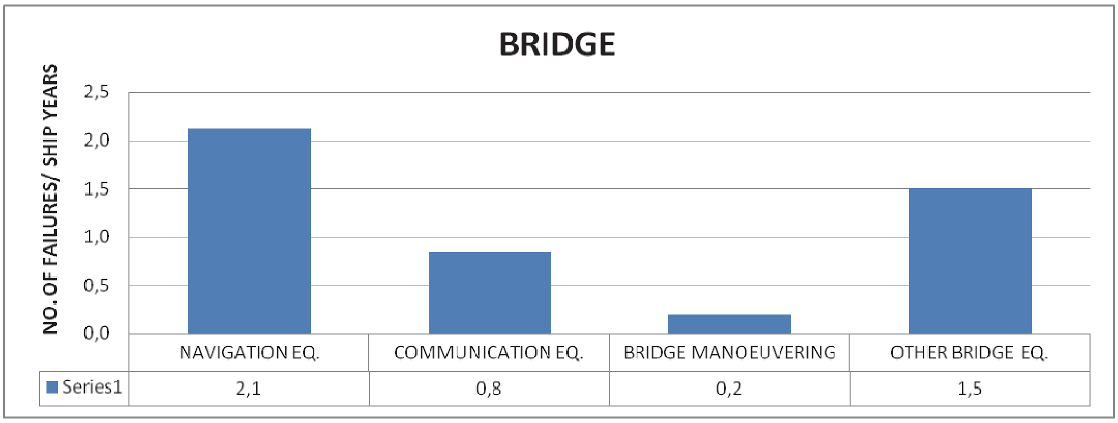

Figure 49: Number of failures divided by the ship years regarding each category of the Bridge for the entire fleet

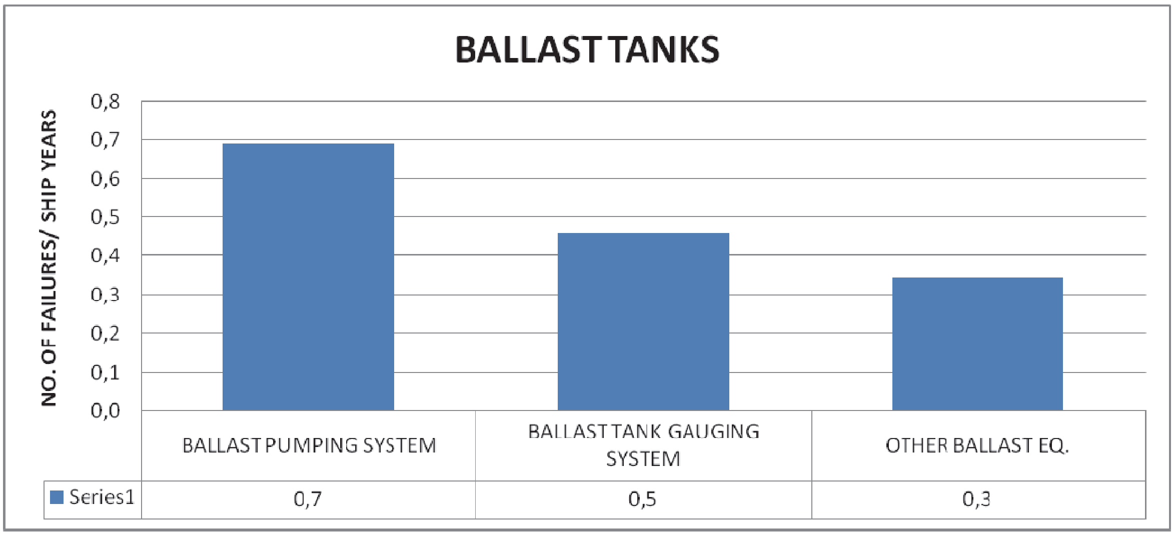

Figure 50: Number of failures divided by the ship years regarding each category of the Ballast Tanks for the entire fleet

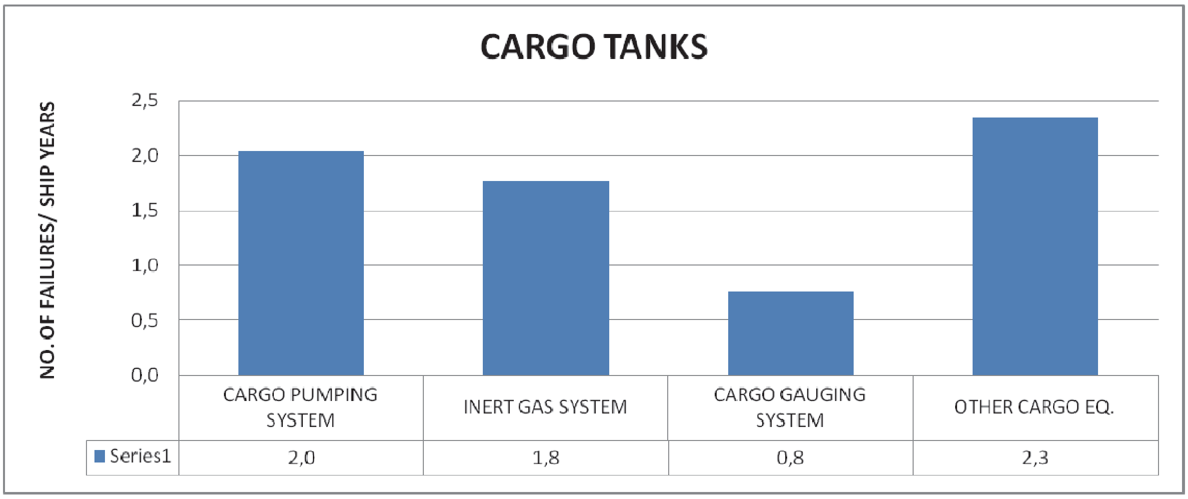

Figure 51: Number of failures divided by the ship years regarding each category of the Cargo Tanks for the entire fleet

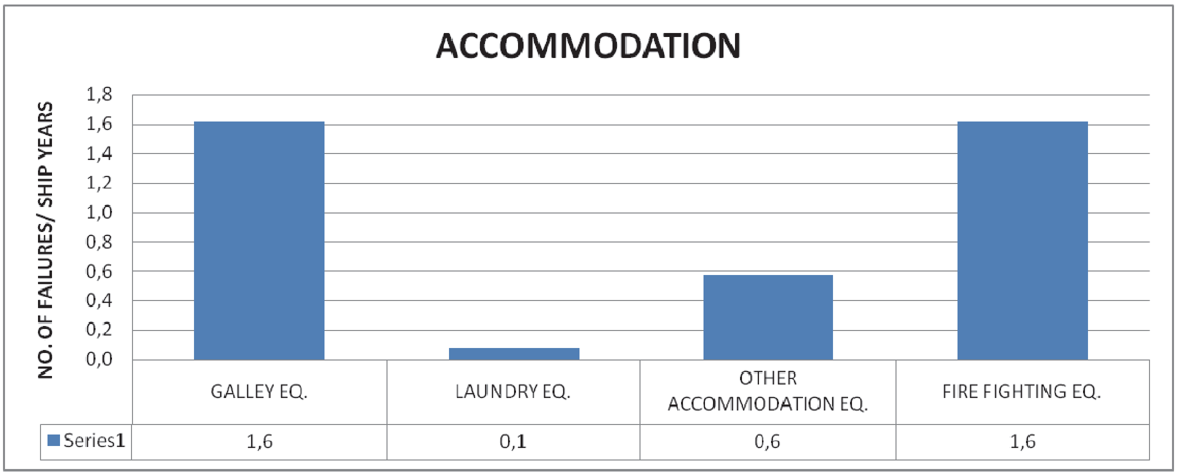

Figure 52: Number of failures divided by the ship years regarding each category of the Accommodation for the entire fleet

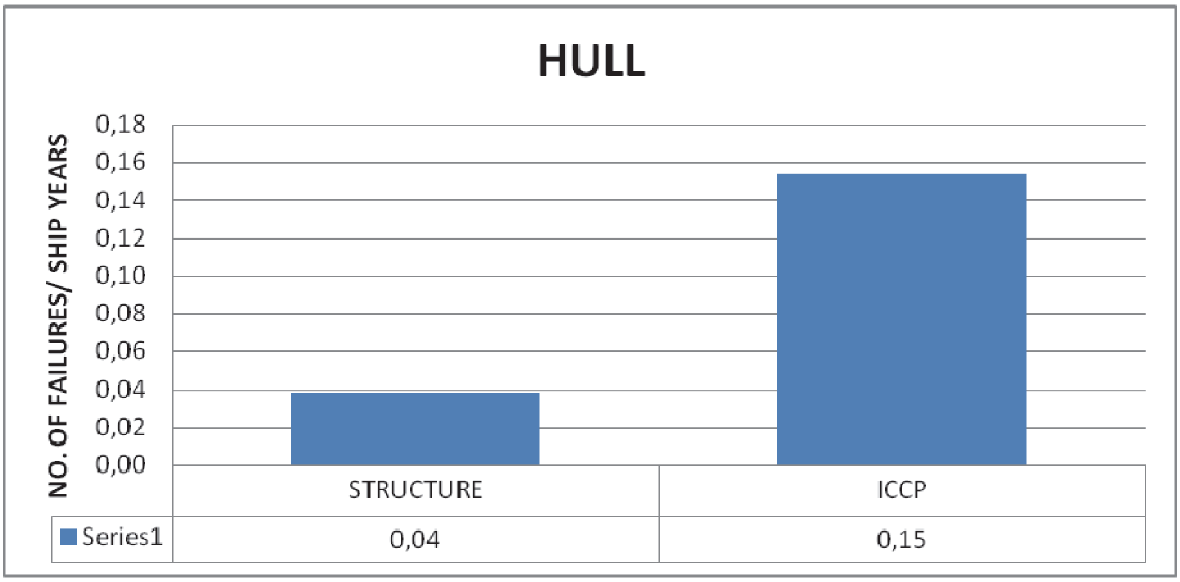

Figure 53: Number of failures divided by the ship years regarding each category of the Hull for the entire fleet

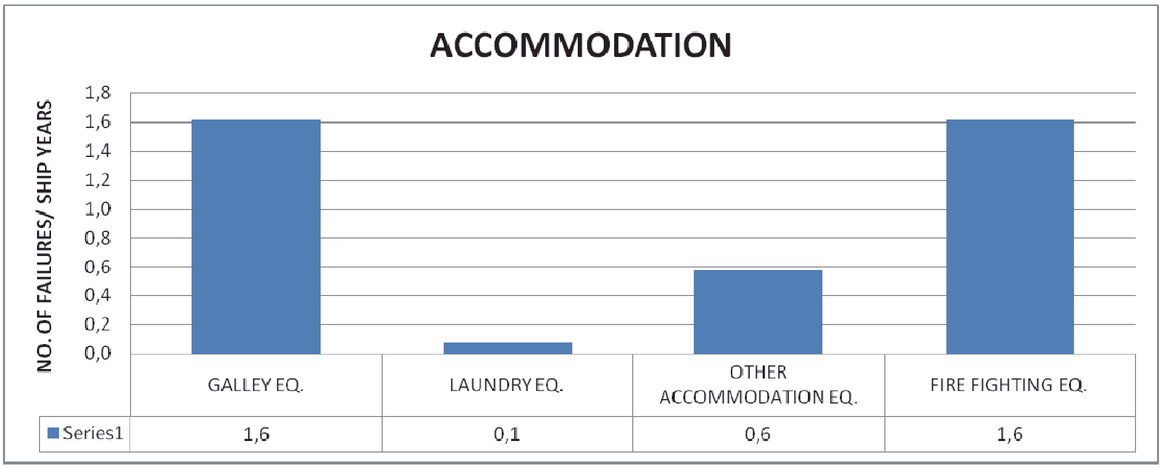

Figure 54: Number of failures divided by the ship years regarding each category of the Bridge for the entire fleet

b) Graphs for Vessel Group No.1

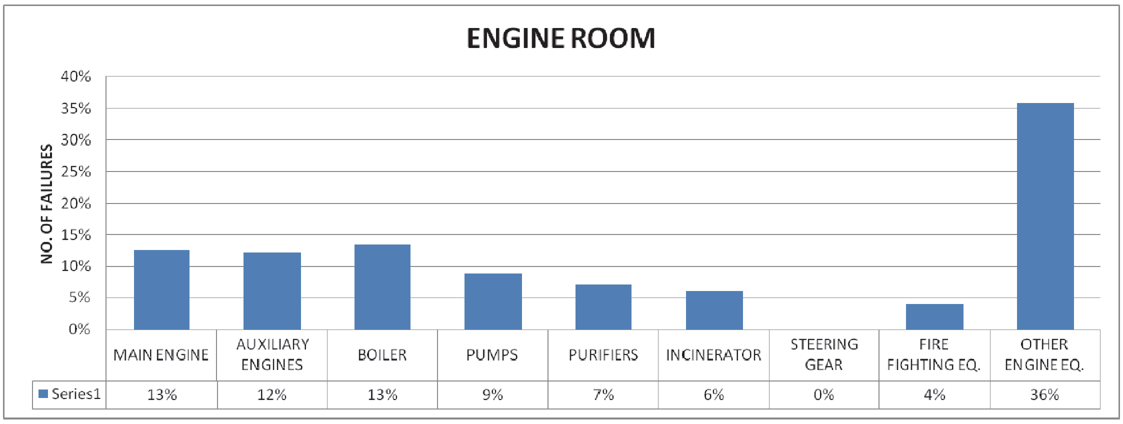

Figure 55: Percentage of failures for Vessel Group No.1 regarding each subcategory of Engine Room

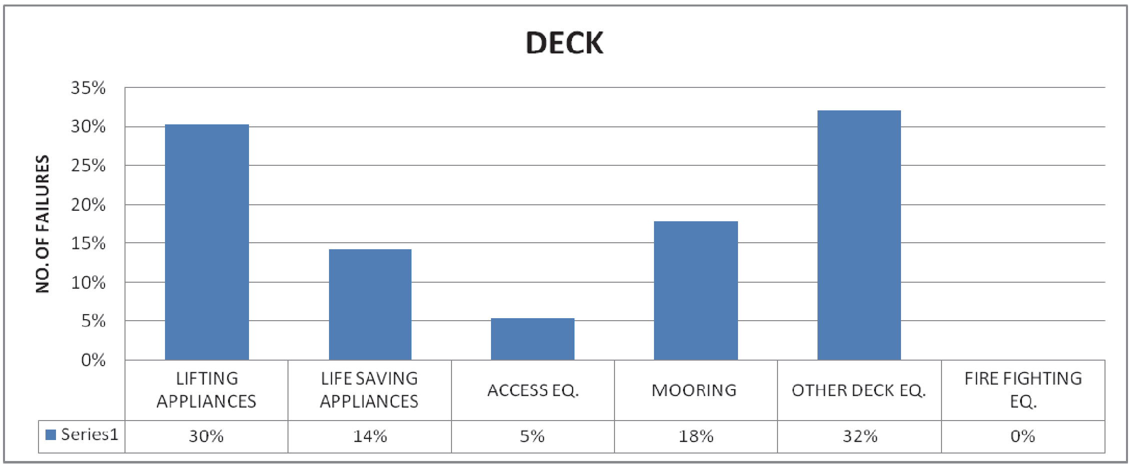

Figure 56: Percentage of failures for Vessel Group No.1 regarding each subcategory of Deck

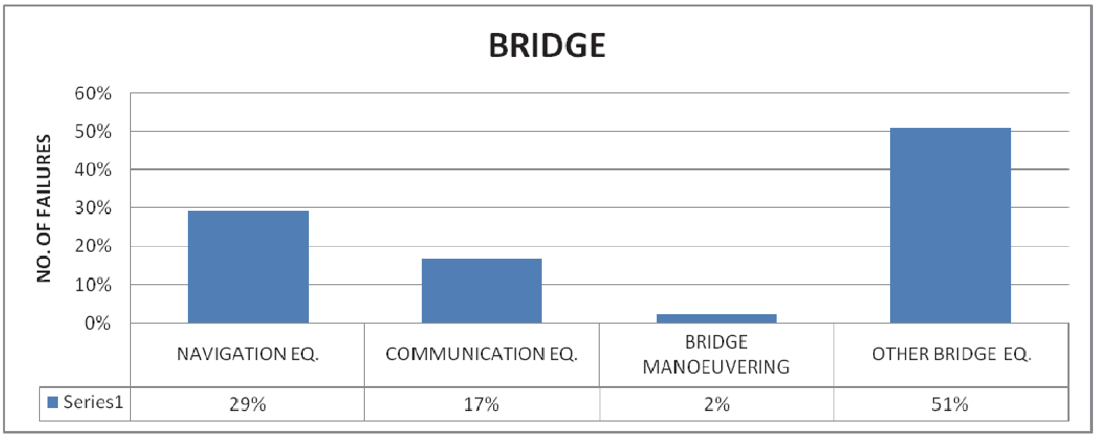

Figure 57: Percentage of failures for Vessel Group No.1 regarding each subcategory of Bridge

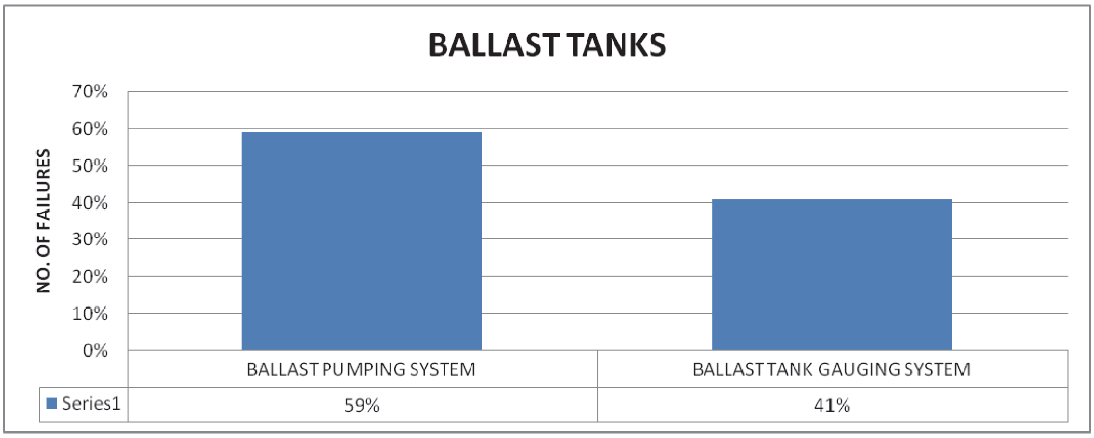

Figure 58: Percentage of failures for Vessel Group No.1 regarding each subcategory of Ballast Tanks

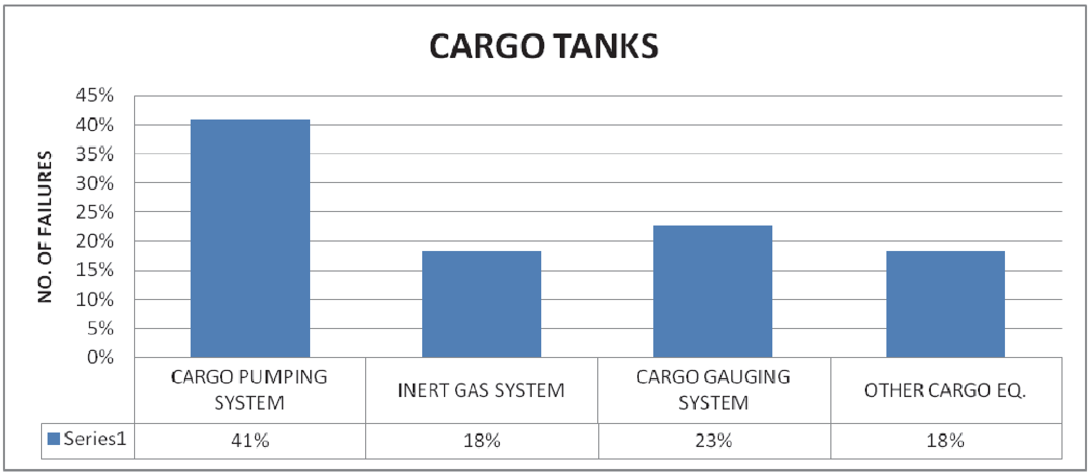

Figure 59: Percentage of failures for Vessel Group No.1 regarding each subcategory of Cargo Tanks

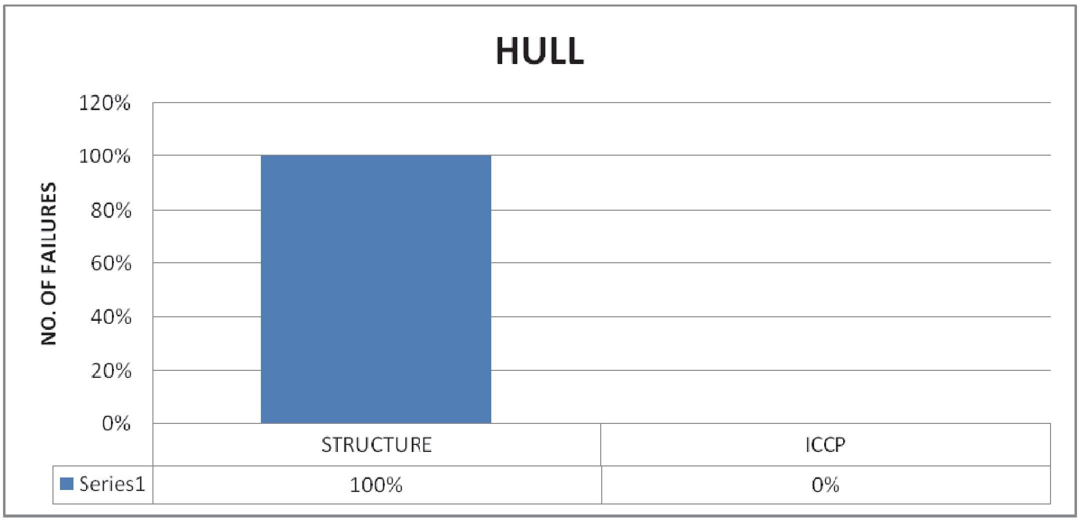

Figure 60: Percentage of failures for Vessel Group No.1 regarding each subcategory of Hull

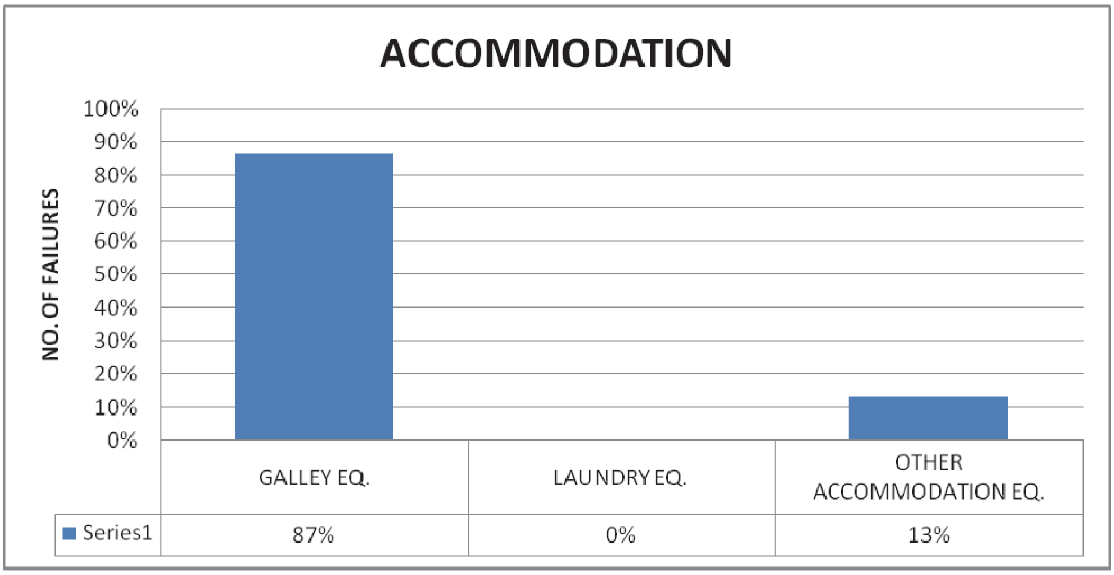

Figure 61: Percentage of failures for Vessel Group No.1 regarding each subcategory of Accommodation

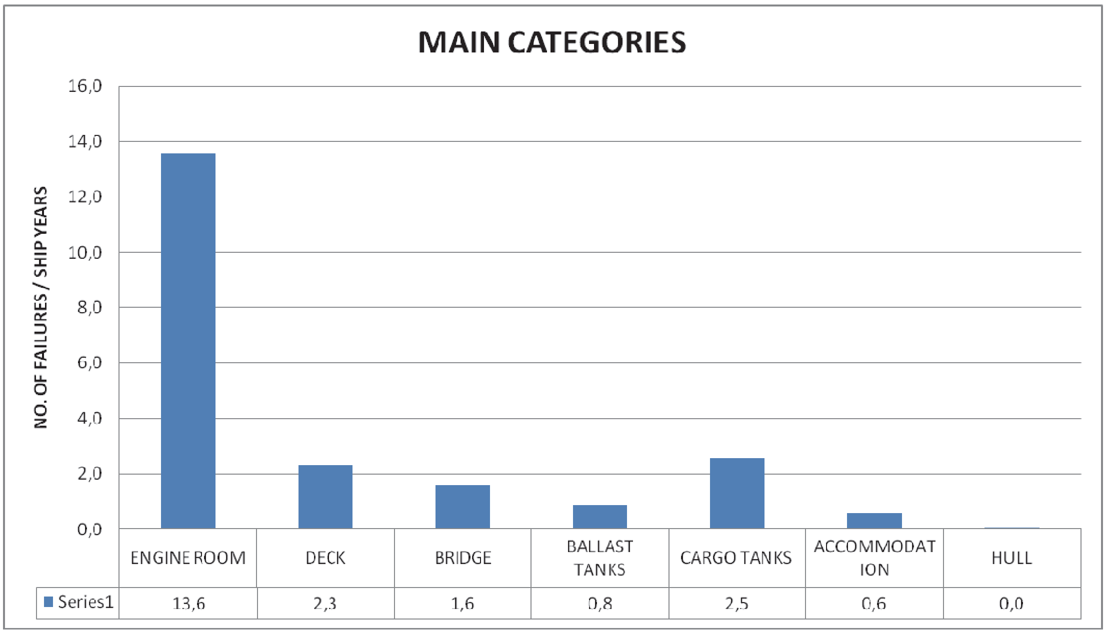

Figure 62: Number of failures divided by the ship years regarding each category of Vessel Group No.1

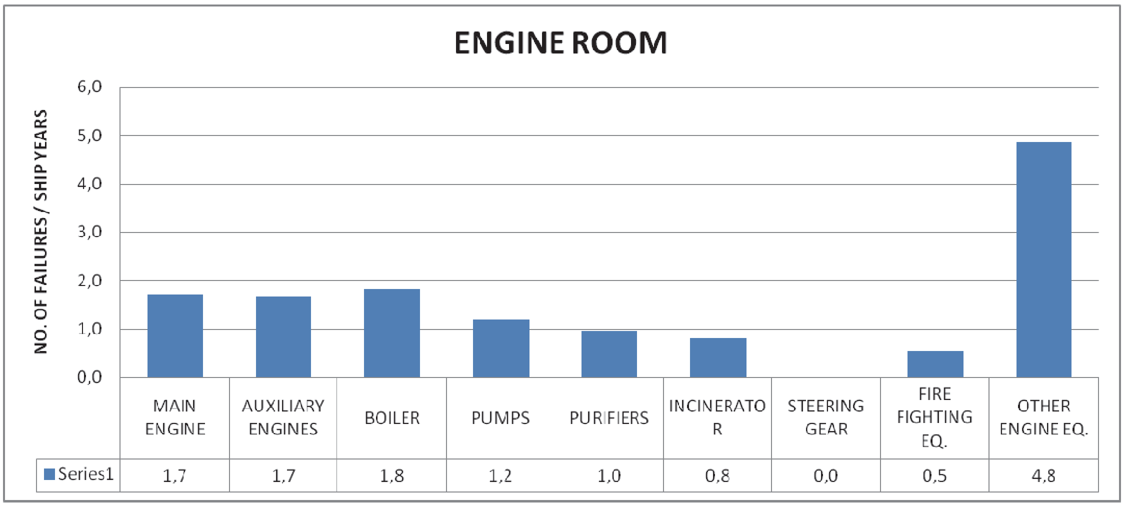

Figure 63: Number of failures divided by the ship years regarding each subcategory of Engine Room of Vessel Group No.1

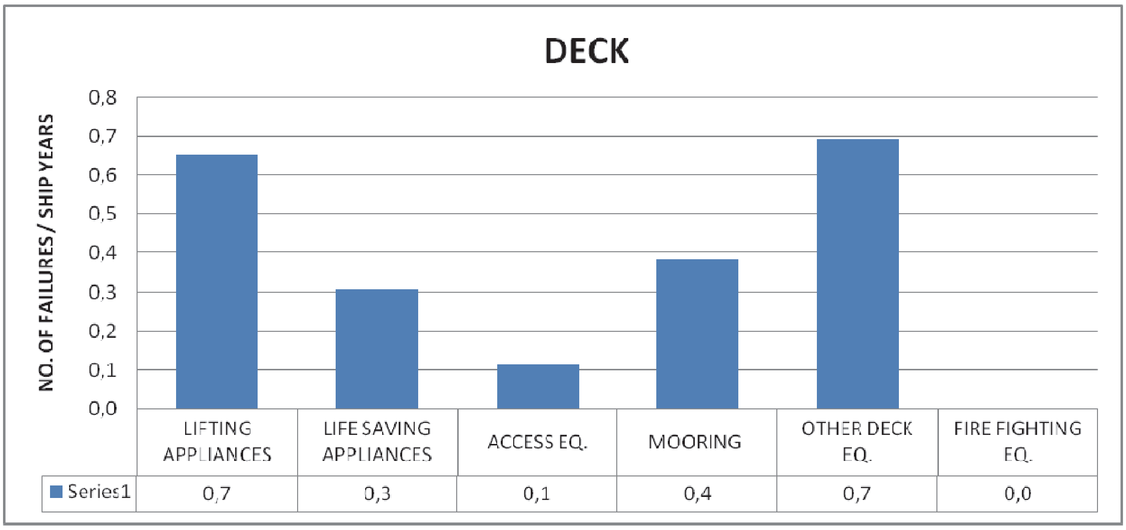

Figure 64: Number of failures divided by the ship years regarding each subcategory of Deck of Vessel Group No.1

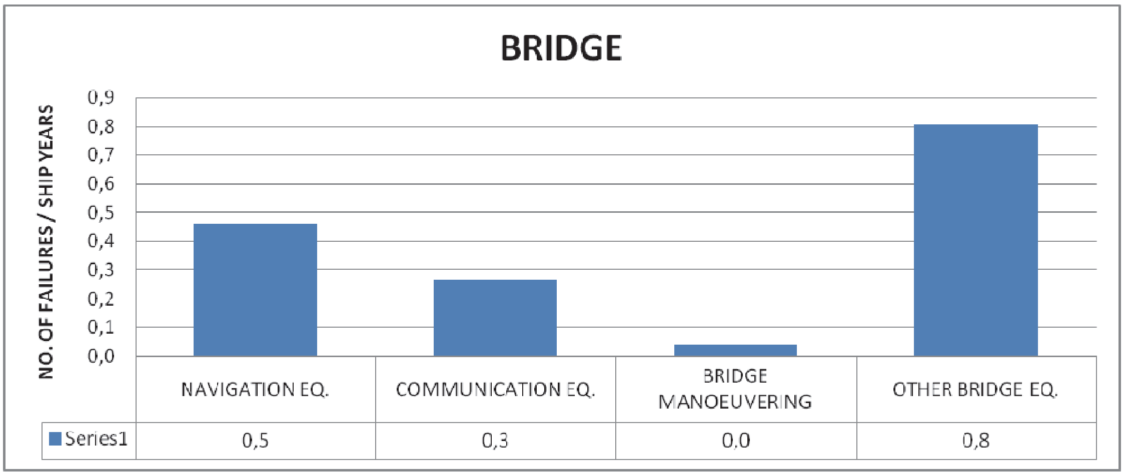

Figure 65: Number of failures divided by the ship years regarding each subcategory of Bridge of Vessel Group No.1

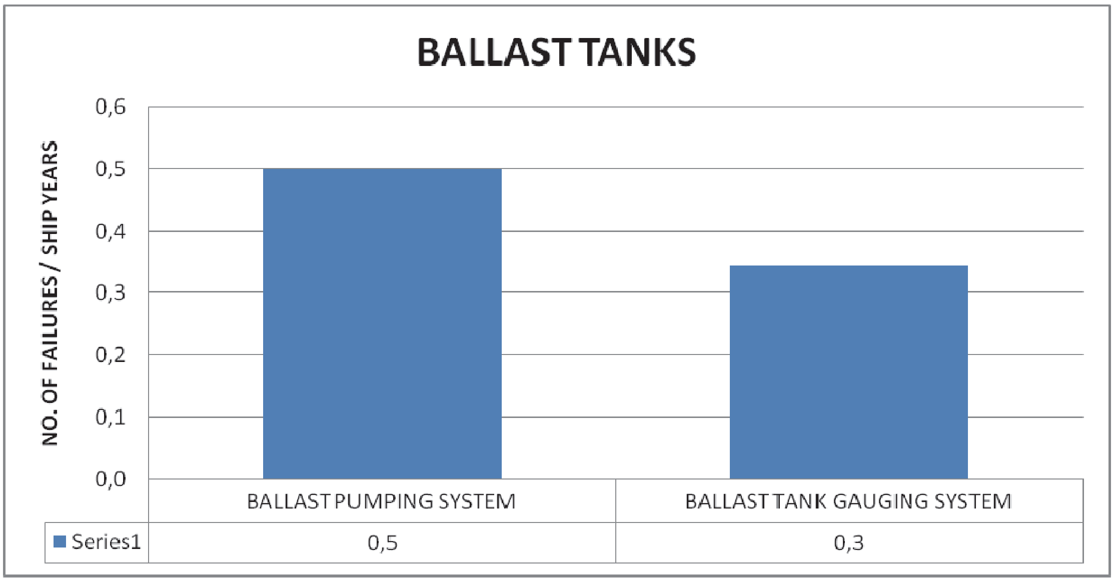

Figure 66: Number of failures divided by the ship years regarding each subcategory of Ballast Tanks of Vessel Group No.1

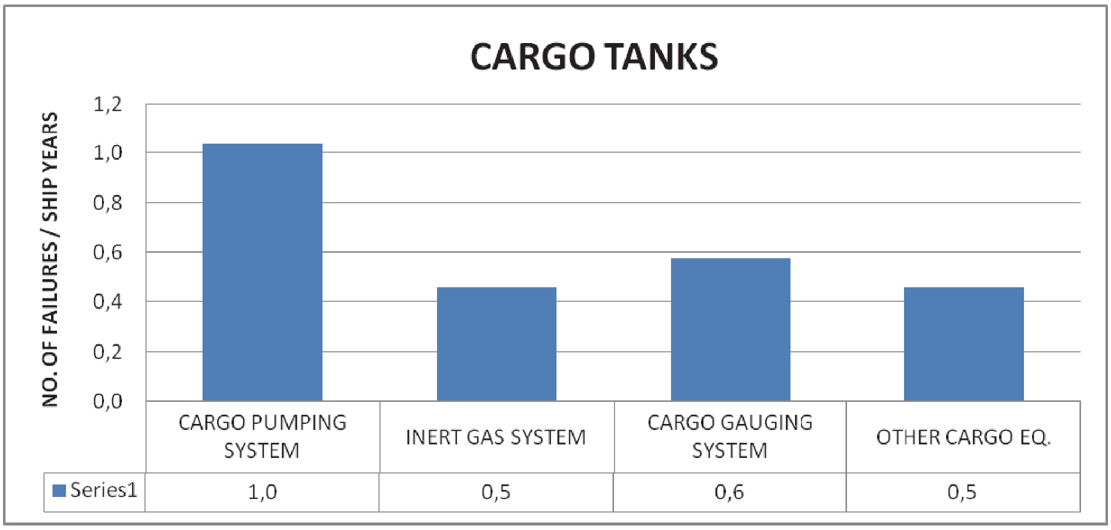

Figure 67: Number of failures divided by the ship years regarding each subcategory of Cargo Tanks of Vessel Group No.1

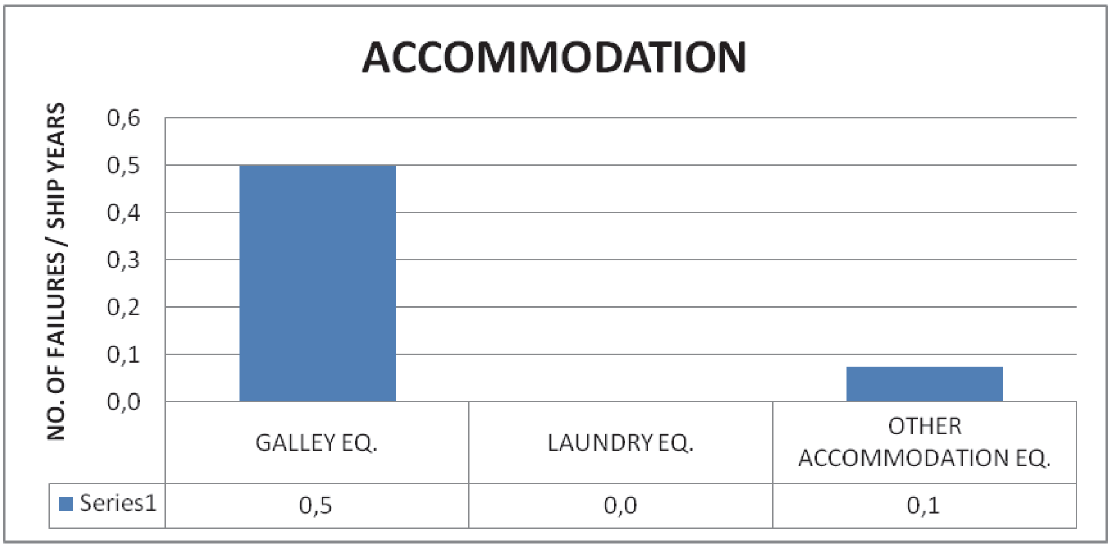

Figure 68: Number of failures divided by the ship years regarding each subcategory of Accommodation of Vessel Group No.1

c) Graphs for Vessel Group No.3

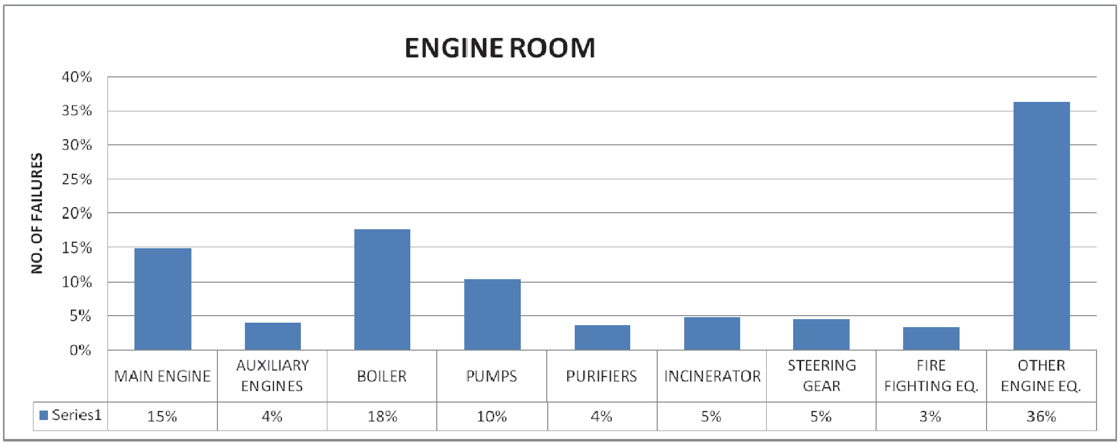

Figure 69: Percentage of failures for Vessel Group No.3 regarding each subcategory of Engine Room

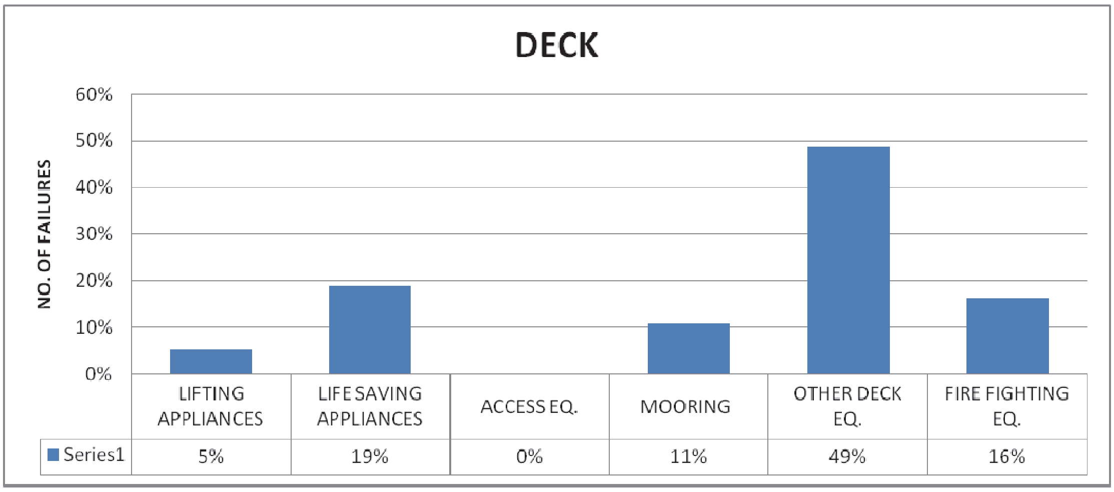

Figure 70: Percentage of failures for Vessel Group No.3 regarding each subcategory of Deck

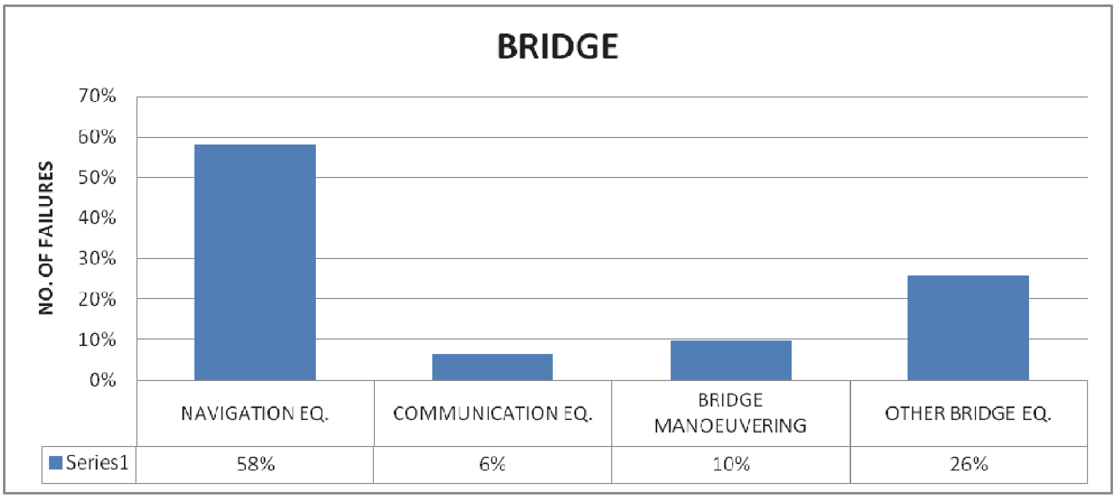

Figure 71: Percentage of failures for Vessel Group No.3 regarding each subcategory of Bridge

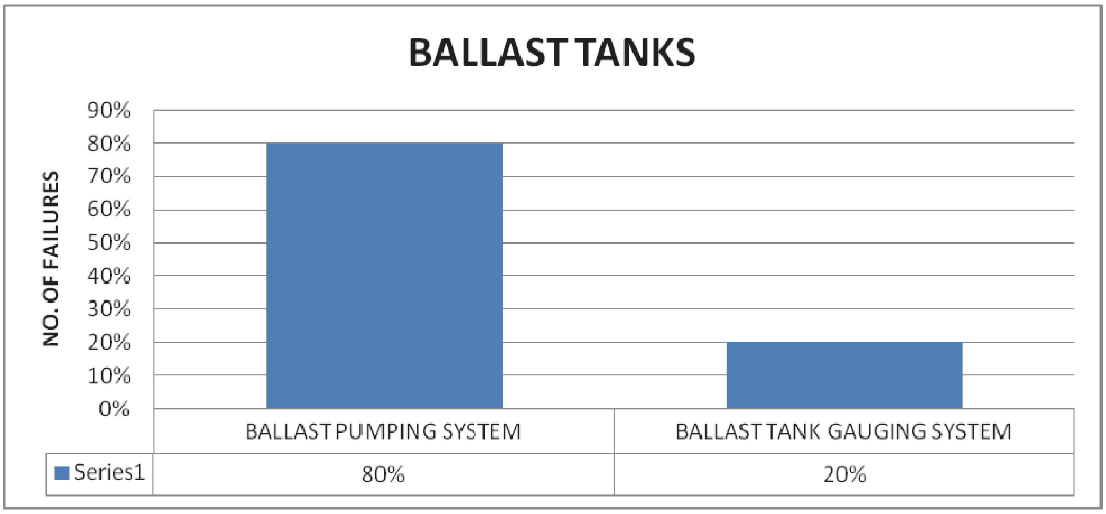

Figure 72: Percentage of failures for Vessel Group No.3 regarding each subcategory of Ballast Tanks

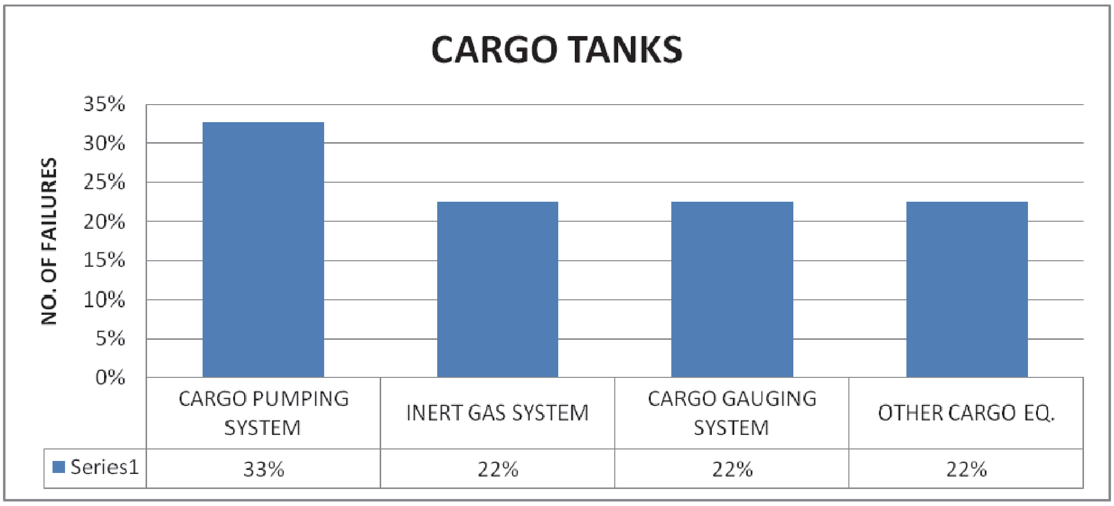

Figure 73: Percentage of failures for Vessel Group No.3 regarding each subcategory of Cargo Tanks

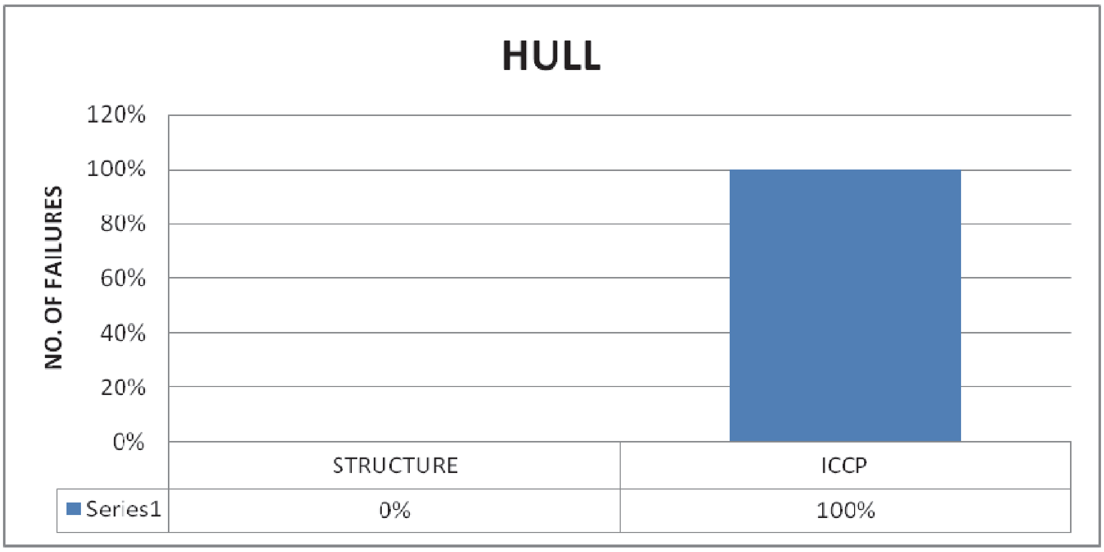

Figure 74: Percentage of failures for Vessel Group No.3 regarding each subcategory of Hull

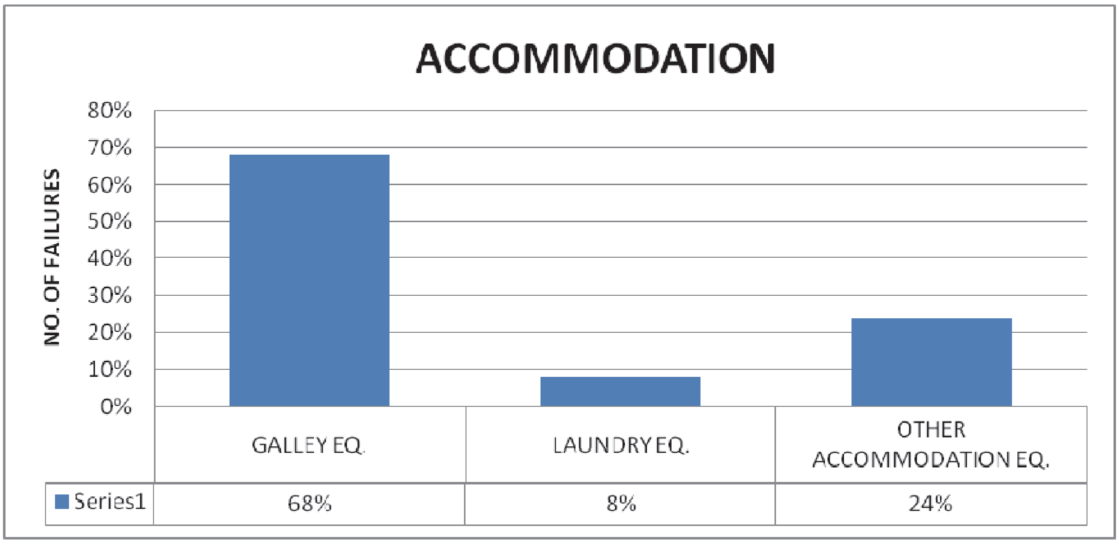

Figure 75: Percentage of failures for Vessel Group No.3 regarding each subcategory of Accommodation

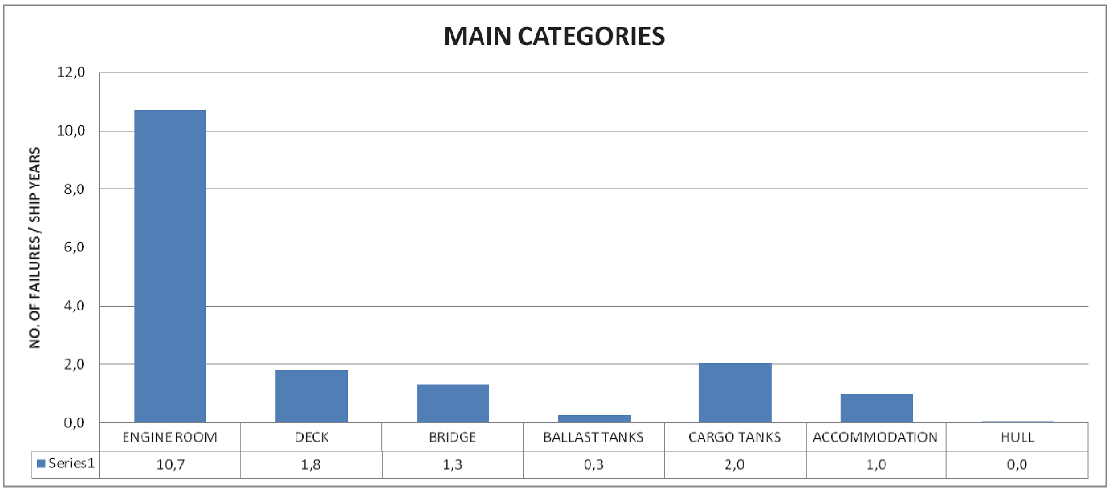

Figure 76: Number of failures divided by the ship years regarding each category of Vessel Group No.3

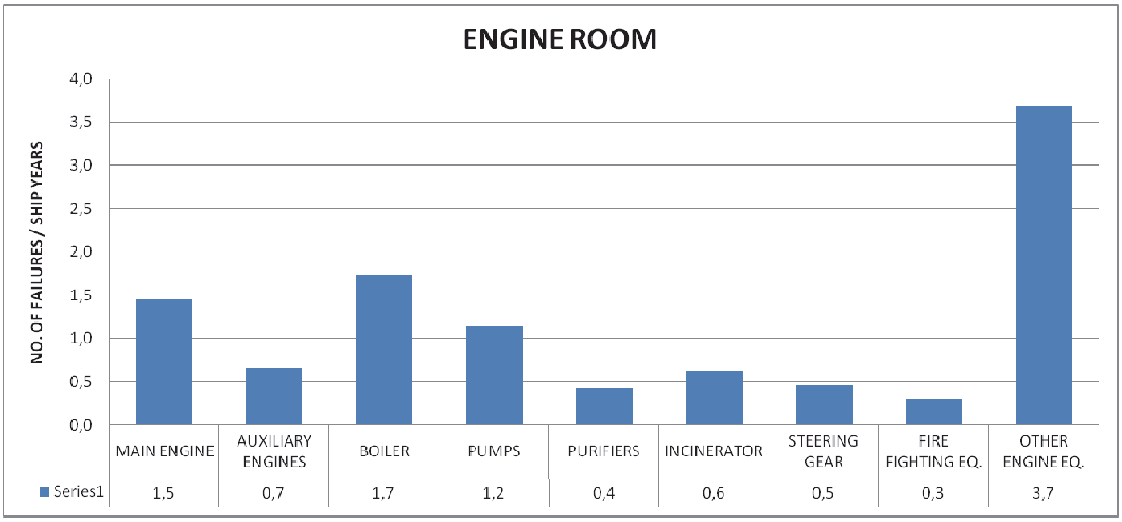

Figure 77: Number of failures divided by the ship years regarding each subcategory of Engine Room of Vessel Group No.3

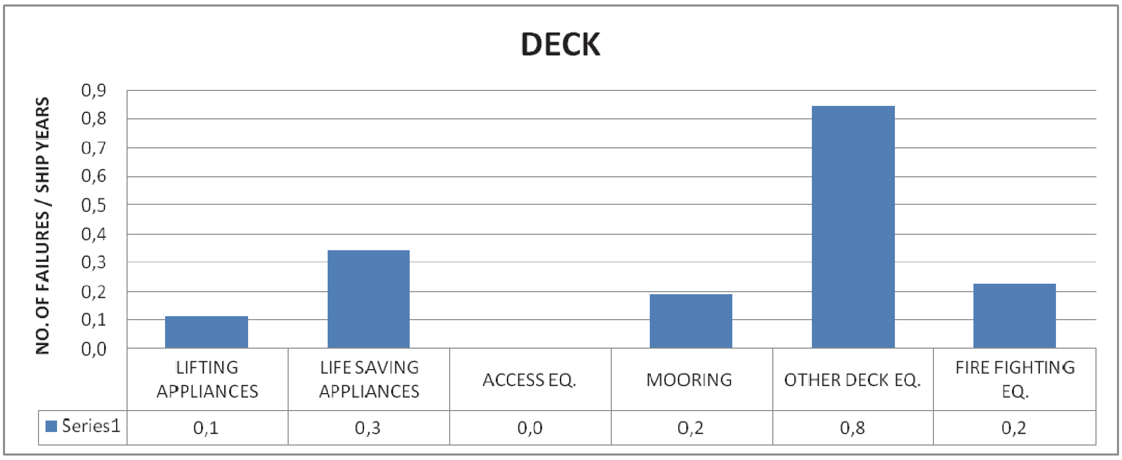

Figure 78: Number of failures divided by the ship years regarding each subcategory of Deck of Vessel Group No.3

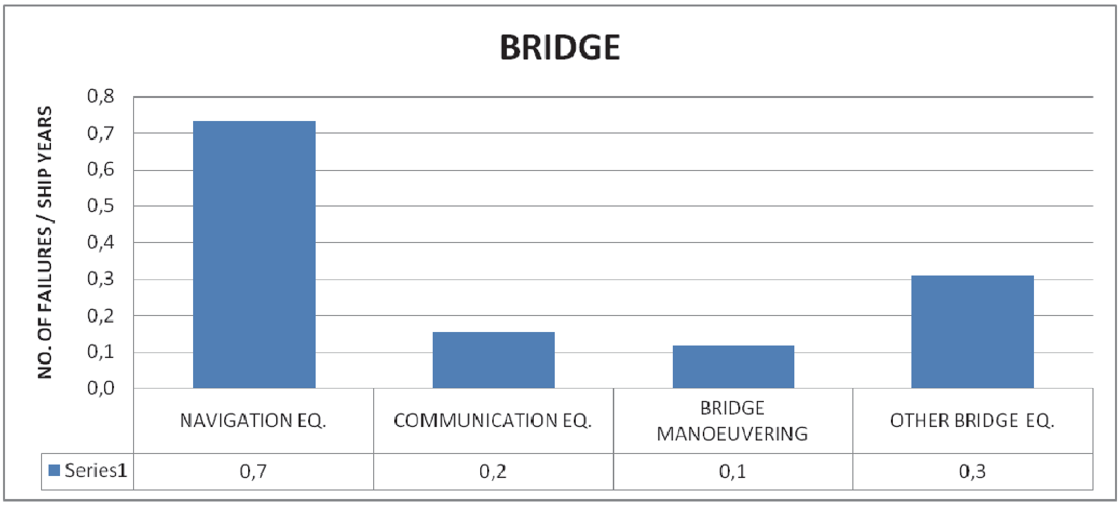

Figure 79: Number of failures divided by the ship years regarding each subcategory of Bridge of Vessel Group No.3

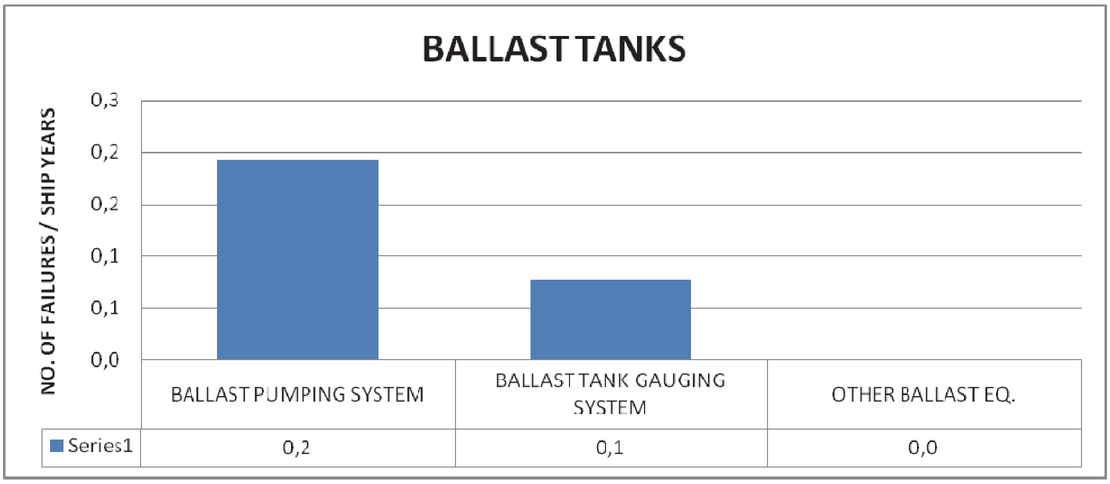

Figure 80: Number of failures divided by the ship years regarding each subcategory of Ballast Tanks of Vessel Group No.3

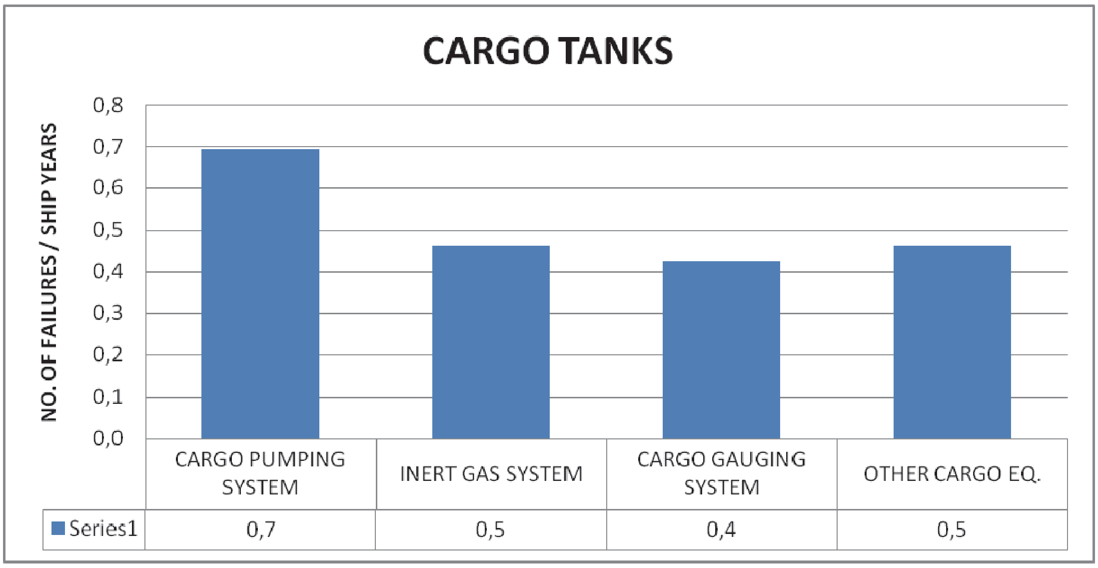

Figure 81: Number of failures divided by the ship years regarding each subcategory of Cargo Tanks of Vessel Group No.3

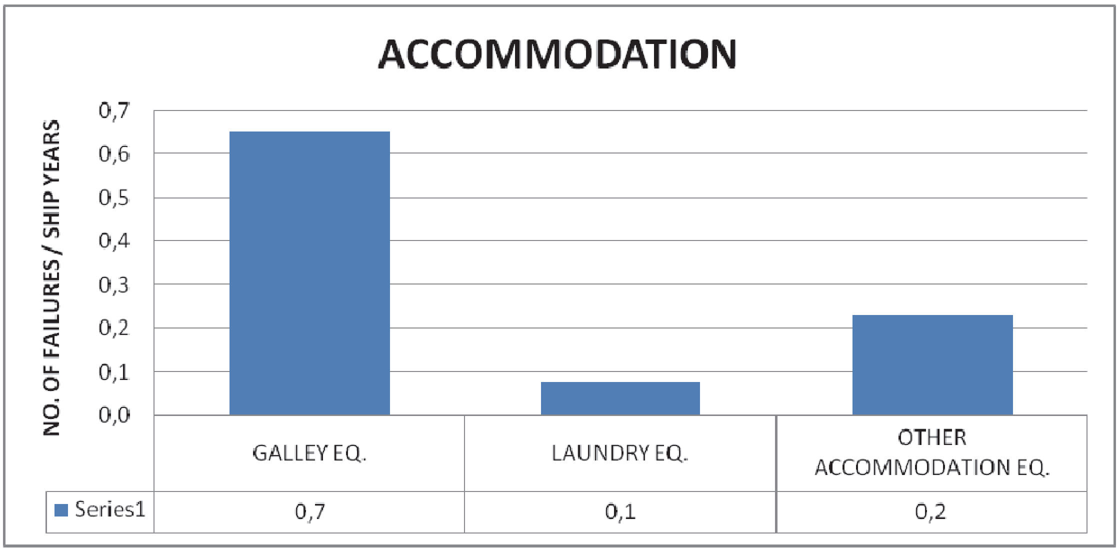

Figure 82: Number of failures divided by the ship years regarding each subcategory of Accommodation of Vessel Group No.3