Modelling Maintenance

Cost Optimised Maintenance in Shipping

S.R.A. Moussault

TUDelft

ANTHONY VEDER

The image on the cover of this thesis is a Mayekawa refrigerant compressor (MYCOM) from the vessel the Coral Star, Anthony Veder, during maintenance in September 2018. Image from Anthony Veder Rederijzaken B.V.

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Cost Optimised Maintenance in Shipping

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This thesis is constructed in collaboration with Anthony Veder.
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Preface

This thesis on cost optimised maintenance in shipping, has been written as part of the Master of Science degree in Marine Technology at the Delft University of Technology. The research was performed under the supervision of Jeroen Pruyn, from the Delft University of Technology, and Geert van IJserloo, from Anthony Veder.

First, I would like to sincerely thank, Jeroen, for his guidance, time, effort, patience and always fast feedback. We had valuable discussions about cost estimation methods, maintenance policies and uncertainty in modelling, amongst others, which all contributed to my research.

Furthermore, I would like to thank, Wim Verhagen, who contributed to the direction and the scope of my research in an early stage, while he was still working at the Delft University of Technology and more recently, while he has since moved to Melbourne, still found the time to read my work and discuss the maintenance calculations and assumptions with me over Skype.

The research was performed in cooperation with Anthony Veder, where I developed a method to calculate the cost of maintenance based on practical failure data. From Anthony Veder, I would especially like to thank Geert, for his guidance, support and advice during the project and Esther, for her never-ending patience, enthusiasm and humour, providing me with literature and discussing about maintenance.

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Sietske Moussault
Delft, April 2020

Summary

The current operational cost estimate applied by shipping management companies is insufficiently valid and accurate for determining the operational budget. Most shipping management companies include scheduled maintenance jobs in the operational cost calculation. Scheduled maintenance does not take unforeseen maintenance into account. In retrospect, unforeseen maintenance makes up approximately 8% of the total operational cost. The estimation of the operational cost can be improved by including the unforeseen maintenance cost.

This research focuses on maintenance cost calculations, based on failure behaviour. Therefore, the (unforeseen) maintenance costs over the lifetime of a vessel are modelled. The Maintenance Cost Model is developed. The model integrates behaviour data from vessels in the maintenance cost estimation. The actual data from the vessels is used to determine the failure behaviour of the systems onboard. This failure behaviour is used to calculate the actual failure rate and mean-time-to-failure. Based on this actual data, the replacement-, off-hire, and reputation cost are calculated. Combined resulting in different total cost per maintenance policy per system. The Maintenance Cost Model generates a system specific, cost based ranking of the maintenance policies. The outcome of the Maintenance Cost Model, this policy ranking, can be used by shipping management companies, to obtain a better substantiated system specific maintenance policy.

The Maintenance Cost Model is validated in a case study. In this case study the achieved cost reductions varied between 0% and 70%, with a conservative average of 16%. Thereafter, the general case study conclusions are assessed in a sensitivity analysis.

The developed model in this research is generally applicable and proves the concept. Improved operational cost calculations lead to better substantiated maintenance policy decision-making. The research concludes with recommendations for future research, which include further expansion of the Maintenance Cost Model and the possibilities to increase the likelihood of the number of replacements.

Contents

Glossary

CoC Condition of Class.

LCC Life Cycle Cost.

MCM Maintenance Cost Model.

MTBF Mean Time Between Failure.

MTTF Mean Time To Failure.

PMS Planned Maintenance System.

SA Sensitivity Analysis.

SIRE Ship Inspection Report Program.

TCO Total Cost of Ownership.

TMSA Tanker Management and Self Assessment.

WACC Weighted Average Cost of Capital.

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Introduction

In this chapter the research of this thesis is explained and motivated. First, in section 1.1 the motivation for this research is explained. Second, in section 1.2 the objectives of the research are presented. Thereafter, the research method is explained in section 1.3 and the scope of the research is discussed in section 1.4. Following, in section 1.5 the implications of the research are elaborated upon. Finally, the structure of this thesis is presented in section 1.6.

1.1. Research Motivation

Anthony Veder is a Dutch gas shipping company, with a long history of involvement in ship owning and gas shipping [2]. For gas shipping companies, especially with a profit objective, it is of the utmost importance to have maximum availability of all assets against the lowest cost. This maximum availability against the lowest cost requires complete control of all assets [60, 66]. Being in complete control of all assets, for Anthony Veder could mean to adopt a more proactive asset management strategy. To be able to be proactive instead of reactive, a predictive model to support business-operations is required [12].

Currently, at Anthony Veder, the operational costs of a gas tanker for the complete lifespan of the vessel, are estimated in the investment decision-making process based upon experience and market-information. A more detailed estimate of the operational costs is only made for short-term periods (approximately five quarters). These estimates are based on the maintenance jobs scheduled for such time-period. Thus, unscheduled repairs are not taken into account when estimating the operational costs. The maintenance costs amount approximately 40% of the total operational cost, of which 20% are for unscheduled repairs [85]. Thus, not taking into account the unscheduled repairs when estimating the operational costs, means that 8% of the total costs are missing. Based upon research in the field of supply-chain and manufacturing engineering (automotive, aerospace industries in particular), there are numerous possibilities to make the total cost calculation more accurate and valid [11, 15, 46, 72].

Besides total cost calculations, the trade-off between repair and replacement is crucial for a proactive management strategy [46]. To be able to make a better substantiated trade-off, information about failure behaviour, the mean-time-to-failure (MTTF), associated down-time and off-hire costs are key. Research into maintenance is widely available [29, 31, 62, 82, 94], however, literature on maintenance in shipping specifically, is more limited [18, 54, 61, 75, 83].

Every (shipping management) company with a profit objective needs to be in complete control of all assets, in order to keep the cost predictable and thus enhance the competitive advantage [38, 60, 79]. For this reason every shipping management company needs a valid and accurate estimate of the total operational cost of a vessel. Therefore, it is essential to be able to accurately predict the costs associated with unscheduled repair and/or replacement of systems onboard a vessel.

Since not all maintenance can be predicted and scheduled [18, 82], shipping companies are estimating operational costs based solely on experience, market-information and scheduled maintenance, which might not be accurate. In operational decision-making, full information and better substantiated calculations are required. This leads to the following problem:

> *”The **current method** applied by shipping management companies, for the estimation of **operational costs** is insufficiently valid and accurate for **proactive ship management**.”*

To prevent any misconception of the defined problem the following three concepts are separately clarified:

- **Current method** - refers to operational costs being estimated based upon experience, market-information and scheduled maintenance jobs
- **Operational costs** - refers to direct and indirect costs of vessel operation
- **Proactive ship management** - refers to a shipping management strategy, based on full information about the scheduled and unscheduled maintenance and their cost.

1.2. Research Objectives

In the context of the preceding sections, the main research question becomes:

> *”To what extent are the **true operational costs** of a vessel improved by applying a **cost-optimised maintenance approach**?”*

To further clarify the defined research question, the concepts and assumptions within the research are the following:

- **True operational costs** : refers to scheduled and unscheduled, direct and indirect costs
- **Cost-optimised maintenance approach** : refers to a maintenance approach, based on system specific maintenance cost predictions

The stated estimate of the true operational costs will provide insights into the unscheduled maintenance costs. These insights can be included in total cost calculation of a vessel, to allow for a better substantiated ship management process. In order to answer the main research question, several supporting research questions are determined. First, the theory behind cost calculations of a vessel needs to be discussed. After that, the indirect cost of vessel operation is examined. Following, the suitable maintenance policies for shipping need to be identified. The next question to be answered is how to combine theory and practice to calculate the cost per maintenance policy, before looking into the improvement of the true operational costs.

1. What are suitable methods to calculate the total cost over the lifetime of a vessel?
2. What are the indirect costs of vessel operation, and how can these costs be quantified?
3. What are the maintenance policies currently applied in shipping, and which of these policies are suitable and relevant to include in this research?
4. What could be a method to be able to calculate and compare the total cost per maintenance policy?
5. What benefits do an equipment specific change in maintenance policy bring Anthony Veder?
6. How does the developed method help improve the general maintenance policy decision-making, and what insights can be gained from this?

Based on the research questions and objectives, the research method and scope can now be defined.

1.3. Research Method

The first step of this research is to describe the state-of-the-art of current research, concerning cost calculation methods and maintenance policies. Based on existing literature the knowledge gap is identified. Thereafter, combining the theory of cost calculation and maintenance, a method is developed, for calculating the total cost per maintenance policy. This method is used to analyse and compare the operational costs induced by maintenance per system or component. Both direct and indirect cost, e.g. replacement and off-hire costs respectively, are included in the research. Not all individual components of the asset, a vessel, will be separately included in the method, a functional subdivision of the systems will be made in accordance with the SFI Group System [78]. The method is developed to sustain the decision-making process before and during operation, to possibly adopt a better substantiated system specific maintenance policy and to obtain an improved operational costs estimate. The purpose of the method is not to substantiate design decisions, as this requires different method requirements.

The objective of this research is to develop a method to estimate the maintenance costs of a vessel, to support a proactive long-term decision-making process. The goal of this method is to capture the main factors that determine unforeseen (maintenance) operational costs of a vessel. Based on the goal and objective, this method should be able to;

- calculate and compare the maintenance share of the total operational cost;
- over the lifetime of a vessel;
- looking from an owners perspective;

- including direct and indirect cost of vessel operation;
- for different maintenance policies.

This research is considered successful when a method is developed, that estimates and compares the total costs of several plausible maintenance policies. This method can be used by shipping management companies, to adopt a better substantiated system specific maintenance policy and to obtain an improved operational costs estimate.

1.4. Scope of the Research

This research covers the unforeseen maintenance costs as part of the operational cost. It will only address maintenance related costs, induced by unforeseen maintenance, and does not include routine maintenance jobs, such as greasing, lubrication, painting, et cetera. The method is developed to make a better informed maintenance policy decision and not to substantiate design decisions. The developed model calculates the maintenance costs, with the focus on the systems and engines onboard, rather than the hull, over the entire life time of one vessel, and does not consider multiple vessels in a fleet. In this research when a system or component is no longer capable to fulfil its required function(s), this is a failure [77]. Zooming in, this means that when a component of a system has failed, this does not necessarily mean the whole system has failed.

1.5. Implications of the Research

Every research has practical, scientific and societal implications. These implications of the maintenance cost model (MCM) are discussed in this section.

1.5.1. Practical Implications

The practical implications of this research are the results and what they mean for the shipping industry as a whole (considering the case study, what they mean specifically for Anthony Veder). The implementation of cost optimised maintenance in shipping, contributes towards a more sustainable and efficient maintenance policy, both financial and environmental.

1.5.2. Scientific Implications

This research aims to take a step forward, towards more efficient maintenance policies in shipping as a whole. The shipping industry can learn from other industries, as other industries might be more inclined or forced to innovate.

This thesis invokes further research into the subject matter. Extensive research in maintenance is available, specific research towards maintenance (policies) in shipping however can be intensified, as there is still room for improvement [54].

1.5.3. Societal Implications

The societal implications are threefold. Cost optimised maintenance contributes to a better environment, as optimised maintenance in general could lead to less material being wasted and less materials being transported to vessels, due to more efficient maintenance planning. Furthermore, better maintained vessels contribute to increased safety and reliability, for the crew of the vessel, as well as the ports the vessels call at and the waters they sail in. Policy decisions can be influenced, as the research contributes towards a cost optimised maintenance policy substantiated with practical data.

1.6. Structure of Thesis

This thesis has the following structure. In chapter 2 the state-of-the-art is outlined, a literature review is presented concerning topics related to this research. Continuing on the literature review, an analysis of the different maintenance policies is presented in chapter 3. Based on the analyses in chapters 2 and 3, in chapter 4 the theory and set-up of the Maintenance Cost Model are specified. Following the theory, chapter 5 elaborates upon the implementation and verification of the model. Thereafter, the application of the model is described in chapter 6. In chapter 7 the influence of decisive parameters of the different maintenance policies are analysed. Based upon all previous, chapter 8 presents the conclusions and finally in chapter 9 recommendations for future research are made.

2

Relevant Research

In the previous chapter the research of this thesis was explained and motivated. Based on the objectives and looking at the goal of the research, the need arises for a method that calculates and evaluates the maintenance share of the operational cost of a vessel from an owners' perspective. Thus, in this chapter a literature review is presented about, maintenance policies, cost estimation methods and the indirect cost of vessel operation.

The literature is categorised by main subject by which it relates to the present research [58]. First, in section 2.1, the state-of-the-art on maintenance policies is reviewed. Thereafter, in section 2.2, existing cost estimation methods are evaluated. Following, in section 2.3 the indirect costs of vessel operation are elaborated upon. This chapter concludes with a summary of the literature research in section 2.4.

2.1. Maintenance Policies

There is an extensive amount of research concerning maintenance policies in industries similar to the shipping industry [1, 4, 10, 14, 17, 22–26, 28, 44, 48, 55, 73, 86, 91, 92, 95], such as the process industry, energy generation industry, manufacturing industry and air [12, 15, 57, 72, 87, 89, 96], rail [11, 63, 79] and road transport industries. However, no literature on cost optimised maintenance, for shipping specifically, was found. These industries are to a certain extend comparable, and thus worthwhile investigating, because these industries as well as the shipping industry, concern complex capital assets, which must be maintained to assure a failure free operation [82]. In recent years different maintenance techniques, a set of activities intended to restore an item to a state in which it can perform its designated functions [29, 31], have been extensively researched, compared and documented [1].

Tinga [81, 82] divides maintenance in three main streams, aggressive maintenance, reactive maintenance and proactive maintenance. According to Tinga [81, 82] aggressive maintenance is adapting the equipment so less maintenance is required. When applying a reactive strategy, the maintenance is performed after a system has failed. When applying a proactive strategy, maintenance is performed before a system fails [68, 81, 82].

De Jonge, Teunter and Tinga [19] compare condition-based maintenance with time-based maintenance, their research is highly useful for this research. Based on the research of Tinga and the research of de Jonge, Teunter, and Tinga [19, 82] proactive maintenance can be opportunistic or preventive. Preventive can again be subdivided in time-based, condition-based, data-driven, to name just a few. To perform maintenance before a system fails, but not waste too much useful life remains the challenge of a proactive maintenance approach. In further literature there are several deviant opinions about what is the most optimal proactive maintenance approach [19, 88, 89]. All, however, proved to be very useful to gain insight in the possibilities to implement a proactive maintenance approach in a cost model of a vessel. Further research into optimal maintenance approaches, needs to prove which maintenance policies are most suitable for stated problem.

Research of Verhagen, de Boer, and Curran [88] illustrates that reliability analysis is useful to identify and plan maintenance. According to Verhagen, de Boer, and Curran reliability analysis is, in the aerospace industry, often limited to statistically based approaches (incorporating failure times as the primary stochastic variable), and they succeed to identify operational factors that influence failure probability. As for the shipping industry cost optimised maintenance is a novel concept, the starting point will be this ”limited” statistical approach, based on failure data. Obviously allowing the possibility to apply the findings of Verhagen, de Boer, and Curran in future research.

In cost optimised maintenance, determining the optimal maintenance policies, solves only half of the equation. Next to maintenance policies, it must also be determined what an optimal cost calculation method is, for calculating the cost over the lifetime of a vessel. This is investigated in the next section.

2.2. Cost Estimation Methods

There are several methods to calculate or estimate the total cost over the lifetime of an asset, used in the field of supply-chain and manufacturing engineering (automotive and aerospace industry in particular) [11, 15, 46, 72]. However, no literature on cost optimised maintenance, for shipping specifically, was found.

Research defines several cost concepts incorporating both direct and indirect costs. The cost calculation method required for this research, needs to include the entire life of an asset, as it concerns maintenance cost estimates [10, 42, 95]. Two common concepts, recurring in literature, for lifetime costing are total cost of ownership (TCO) and life cycle cost (LCC) analysis [37, 39, 42]. These two concepts are related, and both consider costs for the long-term, lifetime of the asset [13, 42, 53, 74]. The possibilities and limitations of these two cost estimation concepts in relation to this research are investigated in the following two sections, first in section 2.2.1 the TCO concept is further researched, and thereafter in section 2.2.2, the LCC concept is reviewed.

2.2.1. Total Cost of Ownership

Founder of the research into the concept of total cost of ownership (TCO) is L. Ellram [32–38]. All research and publications since, are based and continued upon her research and findings and refer to her publications. According to Ellram (1999) [37], TCO is a method for determining what a particular purchase really costs the buyer.

TCO is in the opinion of Ellram (1995) [35] a purchasing tool, created for understanding the true cost of buying a good or service from a supplier, and it very often includes costs as order placement, research and qualification of suppliers, transportation, receiving, inspection, rejection, replacement, downtime caused by failure and disposal costs. In this research a purchasing tool alone is not enough, as the true cost of buying a system are only a small part of calculating the maintenance costs of that system. And for the comparison of different maintenance policies only the costs that vary between the different policies are relevant. Therefore not all acquisition costs, as explained by Ellram (1999, 1995) [35, 37], are relevant for this research, however Ellram's research proved to be very useful to gain insight in the variety of existing acquisition costs.

Further literature research showed that Degraeve, and Roodhooft, and Degraeve, Labro, and Roodhooft, and Bhutta and Huq [8, 20, 21], contributed to the body of knowledge regarding total cost of ownership models being successfully used as comparison selection model. Since this research involves comparison (and thereafter the selection) of system specific maintenance policies, this is an interesting parable between TCO models and this research. Adding to the value of the TCO framework for the development of the maintenance cost model.

According to more research of Ellram [34, 38] the general TCO concept can be applied in a standard model, or a unique model can be developed for a specific asset or purchase. According to Ellram (1993, 1998) [33, 34, 38], and Ferrin and Plank [42] the development of a unique TCO model is a complex task. Since there is no literature of a TCO model for vessels, TCO is not easily and directly applicable for this research. However, the possibility to develop a unique model for a specific asset [34, 38] and the fact that the tool is often used to support management decision-making [93], makes TCO a suitable model for this research [63].

2.2.2. Life Cycle Cost Analysis

The second relevant concept is the concept of life cycle cost (LCC) analysis. An influential publication in the research of (LCC) is the book by Fabrycky, and Blanchard (1991) [39]. All research and publications since 1991, are based and continued upon this research, and refer to this book. According to Fabrycky (1987) and Fabrycky, and Blanchard (1991) [39, 40] a LCC analysis is based on the cost, effectiveness, maintainability, performance, producibility, recyclability, reliability, supportability and quality of an asset. For this research effectiveness, performance, producibility, recyclability and quality as explained by Fabrycky and Blanchard are not relevant. Cost and reliability as explained by Fabrycky and Blanchard are extremely relevant for the maintenance cost model developed in this research.

In the research of Fuller [43] the costs of the LCC method are divided in three main groups, taking into account all costs of acquiring, owning, and disposing of a product or system. When including disposing in the analysis, the analysis goes beyond the life of the product itself and also considers the product service system and the manufacturing process. For this research disposing is less relevant, as disposal costs of a system are not considered to be widely different for a system depending the maintenance policy. The research of Asiedu and Gu [3] showed that within the concept of

LCC the costs of an asset entails the costs to society, the user and the manufacturer and that cost can be classified as management related costs and design related costs. For the moment only the cost for the user are included in this research and as the design phase is outside the scope of this research, only the management related cost as explained by Asiedu and Gu is relevant for this research.

Literature research in other industries illustrated that LCC analysis has been successfully implemented [3, 6, 74, 76, 80]. In the hydrocarbons processing industry failure rate data is used in LCC calculations [6]. This way of incorporating failure data in cost modelling is highly suitable for this research, as failure data is required to predict failure behaviour, on which the maintenance cost calculations are based [4, 14, 73, 96].

2.2.3. Summary of Cost Estimation Methods

Based on previous research both TCO and LCC are useful tools for solving defined problem. Furthermore, it must be said that between the two concepts there are more similarities than differences [42]. The concepts are very much alike [47], it is more the previous applications in which they differ [6, 76, 93], both have useful previous applications, making them both interesting for this research. Summarising:

- TCO was originally developed as a purchasing philosophy, to help understand the costs of an asset. TCO can be applied in an unique model developed for a specific asset [34, 38], it is a tool often used to support management decision-making [93], and allows for comparison and selection [8, 20, 63].
- Current LCC models, based upon literature in the usual academic sources, are generally used in retrospect and consider all costs involved in the development of an asset [76]. In LCC calculations, systems are often divided based on functions [76], this is also common in the shipping industry [7]. Furthermore, LCC allows for the incorporation of failure date [6].
- In literature there are several deviant opinions about the similarities and differences of TCO and LCC. Some say LCC is a way of calculating TCO [42, 47].

In my opinion, a key difference between the two methods, is that LCC is a cost perspective, which includes the cost of development, design, research into the systems, et cetera. Where TCO starts with the purchase of the asset. Resulting in a different ”price”, as TCO takes the acquisition price of the asset, rather than the costs that are involved to develop the asset. This difference is, in my opinion, most apparent in the design and engineering phase. As in LCC there is calculated with the cost of the design and engineering, where in TCO there is calculated with the acquisition price of the finished asset. Based on this main difference, for the development of a cost model for vessels the primary interest is in TCO. Where needed aspects, from the LCC literature that have included failure behaviour in cost calculations [3, 6, 74, 76, 80], will be added to the TCO method.

In long-term cost modelling there is a large number of variables that directly and indirectly affect the real costs creating a level of uncertainty in the outcome of a model [65]. These real costs must be included to allow accurate estimation of total costs of an asset over the entire lifetime [16, 65]. To calculate the current value of future costs, as costs are affected by uncertainty in their future evolution [67], the best choice is to use a figure representative of the company's weighted average cost of capital (WACC) [5] and the inflation rate. The WACC is the rate at which free cash flows are discounted to calculate the net present value [41]. WACC and inflation are universal concepts that can be directly implemented in a shipping specific cost model. In cost modelling direct and indirect costs are also to be included [65], however as these costs are domain-specific, indirect cost of vessel operation require more research.

2.3. Indirect Cost of Vessel Operation

Maintenance during vessel operation, invokes both direct and indirect costs. The direct cost of maintenance, the replacement cost, are straightforward and require no further research. The indirect cost of vessel operation are however, less obvious and thus require some elaboration.

Further literature shows that the indirect effects of unforeseen maintenance in the gas shipping industry, go beyond down-time of the system only [60, 66]. In the tanker business there is an extensive vetting process performed by the cargo-owners, oil majors. These vetting processes consist of Ship Inspection Report Program (SIRE) inspections, which are inspections of individual vessels, as well as Tanker Management and Self Assessment (TMSA) audits, in which the whole management of the fleet and office are examined [9, 51]. Since the TMSA audits examine the whole fleet, this means a defect or negative inspection report on a vessel not utilised by the concerning oil major may negatively affect the outcome of an audit by this oil major. Due to this intensive vetting climate in the gas shipping industry unforeseen maintenance can lead to loss of reputation, loss of hire, or even loss of a long-term time-charter, therefore vetting inspections create a strong commercial incentive for ship owners and/or management companies [56].

Between loss of reputation and loss of hire there is a difference. Consistently not sailing, vessels always being in poor condition, has an effect on contracts down the line, not only on the immediate contract. This could be seen as a disturbed relationship with the customer, and is considered as long term reputation damage, which is not measurable on vessel level [49, 85]. Long term reputation damage exists more on fleet level, even more so, as certain clients evaluate the whole fleet and evaluate the management-system [9, 51, 56].
As this research focuses on a method for a single vessel, long term reputation damage is not included. A possibility for future development of the method, when potentially expanding the method to fleet level, could be to include the long term reputation damage on the basis of the figures from a company specific risk matrix [6, 10]. Next to the long term reputation damage, there is also the short term reputation cost. Short term reputation costs, are the reputation costs directly induced by a failure on that vessel. This can be, loss of hire or being less flexible at the spot-market as it is not possible to transport all cargo of all clients. How to quantify these short term reputation costs, the indirect costs of a failure?

The costs induced by the ”vetting risk” of a failure can be expressed in different ways

[50, 85]. However there is one that is measurable for every failure and therefore this way of calculating the indirect cost of a failure is chosen [49, 84, 85]. The measurable effect of the vetting risk is the requirement of a ”Condition of Class” (CoC). The failure of a system or component can mean that the vessel no longer complies with the rules of the classification societies. This would mean that the ”Class Certificate” of the vessel is revoked, meaning that the vessel can no longer sail. However, in this case it is possible to receive a CoC, meaning that a class surveyor allows the vessel to continue to sail for a certain period of time. To be able to retain the class, the failure needs to be repaired within a specified period. When a CoC is the result of a failure, the vessel is allowed to sail according to class. However clients may nevertheless impose consequences. These consequences can mean that a certain client does not want to hire a certain vessel.

It is obvious that no sailing, in whichever form, has a direct negative impact on possibility to generate income for a vessel. Based on these findings it is apparent that the indirect costs resulting from a rejection of a client need to be included in the cost model.

2.4. Concluding Remarks

In this chapter, a review of three topics in literature (cost estimation methods for vessels, maintenance and indirect cost of vessel operation) was given. Based on these three reviews, conclusions can be drawn for the next steps in this research:

- In literature different maintenance policies have not yet been researched for the shipping industry. Further research needs to prove which maintenance policies are most suitable for stated problem. Based upon the research of Ahmad and Kamaruddin [1], it is eminent that a proactive maintenance policy is a suitable starting point for this further research.

- For the development of a cost model for vessels the primary interest is in TCO. Where needed aspects, from the LCC literature that have included failure behaviour in cost calculations [3, 6, 74, 76, 80], will be added to the TCO method. Focusing on TCO seems the best approach for an unique maintenance cost model for vessels. The cost model approaches almost exact the requirements of the maintenance cost model. Which is to calculate the operational cost of a vessel for different maintenance policies. Continuing on the research of Fabrycky and Blanchard and Ellram [35, 39] this research will, not for the first time, integrate the two existing methods, TCO and LCC, into a total cost model.

- The indirect costs resulting from a rejection of a oil major need to be included in the cost model. The requirement of a ”Condition of Class” (CoC) is the most obvious way to quantify these indirect costs of vessel operation.

Based on the conclusions of the analysis of existing literature, the first two research questions have been answered.

1. *What are suitable methods to calculate the total cost over the lifetime of a vessel?*

The answer to this first research question can be found in the analysis presented in this chapter, and in short, as presented at bullet point number two of the concluding remarks, both TCO and LCC are suitable to calculate the total cost over the lifetime

of a vessel. For the development of the cost model for vessels in this research the primary interest is in TCO.
The second research question was:

2. What are the indirect costs of vessel operation, and how can these costs be quantified?

The answer to this question was presented in this chapter, and in short as presented at bullet point number three of the concluding remarks, indirect costs, such as loss of hire, can be quantified, based on the requirement of a CoC. Based on the above, the next step is to investigate suitable maintenance policies for defined problem. This further research into maintenance can be found in the next chapter, chapter 3.

3

Maintenance Policies

The previous chapter describes the general maintenance techniques and policies as described in academic literature. In this chapter a more in depth analysis of the different types of maintenance policies is made, whereafter the suitability of the different polices to the defined problem is analysed. First, in section 3.1 a categorisation of the several maintenance policies is presented, following in sections 3.2 up to and including 3.5, the different policies are further analysed. Whereafter, in section 3.6 the suitability and relevance, of all explained maintenance policies, to this research problem are investigated. This chapter concludes with a summary of the maintenance policy analysis in section 3.7.

3.1. Classification of Maintenance Policies

A large variety of definitions, names, distinctions and classifications of maintenance exist. In this section the definitions and classification as used in this research are established. This classification is largely based on the classification as proposed by Tinga [82], and expanded with a condition-based maintenance branch based upon information from Tinga [81] and Veldman et al. [86].

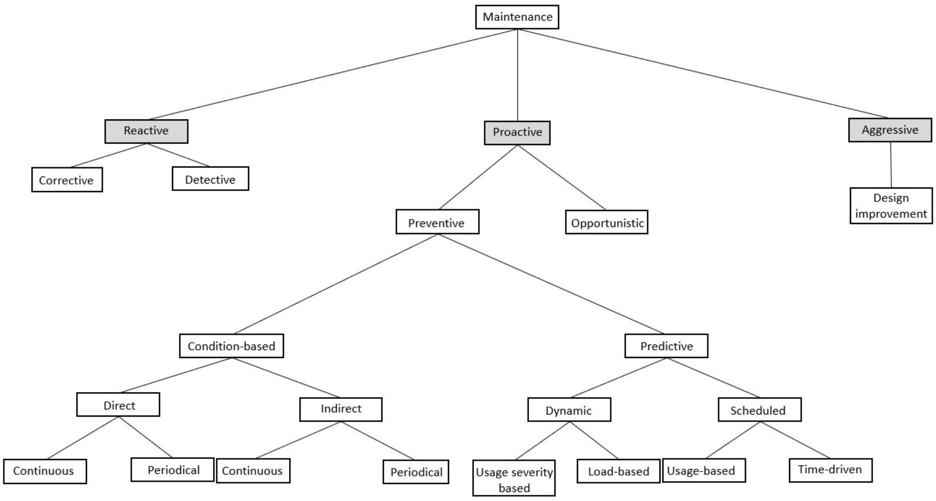


Figure 3.1: Classification of Maintenance Policies

In figure 3.1 the subdivision between the different policies is illustrated. As shown in the overview, maintenance is divided in three main branches, namely *reactive*, *proactive* and *aggressive*. In the following sections these maintenance policies per branch are explained in more detail. First, in section 3.2 the aggressive maintenance policy is explained. Following, in section 3.3 the reactive maintenance policies are explained. And finally in sections 3.4 and 3.5, the proactive maintenance policies are elaborated upon.

3.2. Aggressive Maintenance

Aggressive maintenance involves adapting the equipment, by redesign or modification, to decrease the amount of failures. An improved (sub)system often requires less maintenance [82]. Aggressive maintenance can be beneficial in multi-component systems, it is applied in railway, aerospace and shipping maintenance amongst others [62, 79, 91]. Since the ship design phase is outside the scope of this research, aggressive maintenance is not further elaborated upon, as redesign is considered part of the design phase.

3.3. Reactive Maintenance

Reactive maintenance is maintenance that is performed only after a failure has occurred. The big advantage of reactive maintenance compared to proactive maintenance is therefore, that no remaining lifetime of the (sub)system is wasted. The branch of reactive maintenance is divided in *corrective* and *detective* maintenance.

Corrective maintenance is applied after a failure manifests itself. Corrective maintenance can be more expensive than preventive maintenance because failures often occur unexpected, which then leads to a higher chance of more severe consequences and longer down-time of the (sub)system [19]. However, when the failure does not directly lead to down-time of the (sub)system corrective maintenance can be a very profitable maintenance policy, since no useful life of the (sub)system is wasted and no data collection or prediction model is required to predict the optimal maintenance moment.

Detective maintenance only applies to thus-far unrevealed failures. Normally unrevealed failures can only appear on protective devices, for instance sensors and alarms. The failure is only detected when a test reveals that the device has failed [82].

Both corrective and detective maintenance are a costless policy since less data needs to be collected, stored and/or monitored. Furthermore, no remaining useful life of the (sub)system is wasted. However, as explained above the maintenance itself can be more expensive.

3.4. Proactive Maintenance

Proactive maintenance, is maintenance that is performed before a system fails. The proactive maintenance policies are divided in *preventive* and *opportunistic* maintenance.

Preventive maintenance is to prevent unexpected breakdown of the (sub)system, and is aimed to be performed shortly before a potential failure occurs, thus without spoiling too much remaining lifetime [11]. The difficulty of the policy therewith lies in determining the optimal moment of maintenance. Therefore preventive maintenance contains several different maintenance policies, all aimed at determining the optimal moment of maintenance. As illustrated by figure 3.1 the proactive maintenance branch is a lot larger than the reactive or aggressive branch. This is because there are numerous preventive maintenance policies. These different preventive maintenance policies are further explained in section 3.5.

Opportunistic maintenance is also performed before a system fails, however in this policy the determination of the maintenance moment is not influenced by the system that will receive maintenance, but by other external factors [23, 25]. Opportunistic maintenance is about clustering maintenance tasks to obtain time and/or cost benefits. An opportunity is any moment in time at which a (sub)system can be maintained preventively without obtaining extra cost for downtime of the (sub)system. Opportunistic maintenance is beneficial for continuously used systems for which downtime costs are high. Examples of applications of opportunistic maintenance are large assets that are used continuously, such as air-crafts, trains and power generators at offshore production platforms [4, 11, 26]. In ship maintenance the compulsory 2,5 year class survey provides such an opportunity. For opportunistic maintenance no data needs to be collected, stored and/or monitored, also the implementation costs of the policy are zero. However, as the maintenance is performed before the failure occurs remaining useful life of the (sub)system is wasted.

3.5. Preventive Maintenance

Preventive maintenance can be *condition-based* or *predictive*. In condition-based maintenance the condition of the (sub)system is monitored to determine the optimal moment of maintenance, in this policy the maintenance is normally performed when it is actually necessary. In predictive maintenance other methods than condition monitoring are used to determine the optimal interval for maintenance. To perform maintenance before a system fails, but not waste too much useful life remains the challenge of a predictive maintenance approach [46, 88].

3.5.1. Condition-Based Maintenance

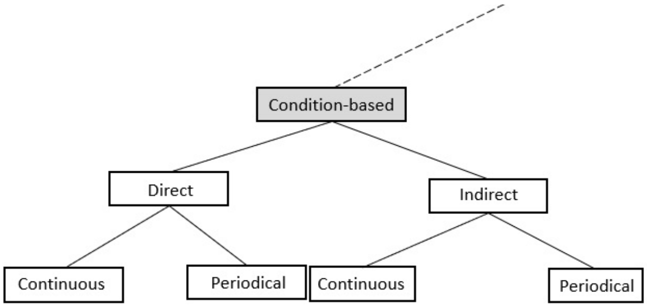


Figure 3.2: Classification of Condition-Based Monitoring Maintenance Policies

The condition of a (sub)system can be monitored by sensors or inspection. Monitoring is defined as: "An activity which is intended to observe the actual state of an item" (SS-EN 13306, 2001, p.16). As can be seen in figure 3.2 condition monitoring can be performed *direct* or *indirect*.

- **Direct monitoring** is based on condition indicators, this monitoring is performed by sensors to directly monitor the condition of the (sub)system. Examples are noise data, vibration data, crack length measurements and wear particles. [86]
- **Indirect monitoring** is based on condition predictors, here performance parameters are monitored. Examples of performance parameters are pressure, temperature and flow. [86]

Both direct and indirect monitoring can be performed *periodical* or *continuous*. **Periodic monitoring** is performed at certain intervals, based on for example time, running-hours or work-shifts. **Continuous monitoring** is performed automatically and continuous, usually this monitoring is performed by sensors that are installed and permanent [1, 81].

Depending on how accurate the prediction of a failure needs to be, a large amount of data is required to be compared and analysed, to be able to detect anomalies. It differs slightly between the different types of condition monitoring, but in general several years of data need to be collected to be able to accurately predict failures [82, 88, 90]. This is illustrated in figure 3.3. In this graph the point in time a potential failure can be detected is called P, the point of the actual failure is called F. The time period between these two points is the P-F interval and this is the time-window in which preventive maintenance can take place [82].

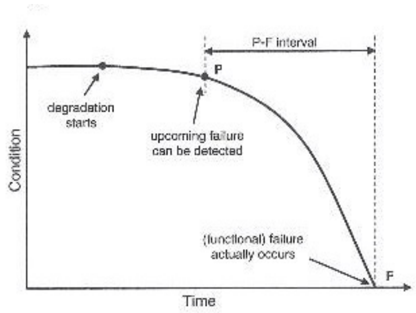


Figure 3.3: Relation Between the Observance of a Potential Failure(P) and the Actual Failure(F) [82]

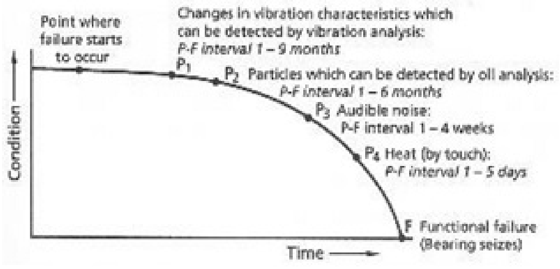


Figure 3.4: Different Potential Failures which can be detected of a Roller Bearing [94]

In figure 3.4 the different condition measurements of a roller bearing that can precede one failure mode are presented within this P-F interval. Here it is illustrated that different types of condition monitoring result in different locations of point P, thus resulting in different P-F intervals. The more data there has been collected and stored, the earlier an anomaly can be detected, meaning the closer point P moves to the point where the degradation started, therewith enlarging the P-F interval. Thus, a larger amount of collected data leads to an earlier and more accurate prediction of the potential failure. [94]

However, for indirect monitoring it is also possible to compare measurements to recommendations made by the manufacturer. Manufactures do for example make recommendations about lube oil samples and exhaust gas ranges. When comparison to recommended data is used to predict failures, less data needs to be collected and stored [84].

As the maintenance is performed before a failure occurs remaining useful life of the (sub)system is wasted. The costs of a condition-based maintenance policy are high, especially when several years of monitoring and data comparison are required.

3.5.2. Predictive Maintenance

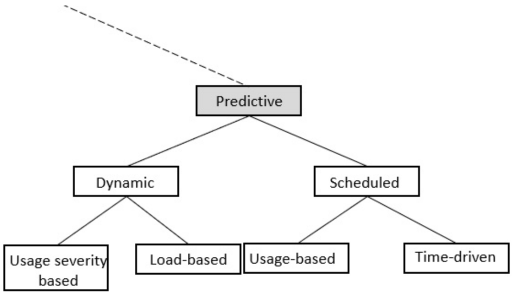


Figure 3.5: Classification of Predictive Maintenance Policies

Predictive maintenance can be time-based, usage-based and load-based. As illustrated in figure 3.5 predictive maintenance can be *scheduled* or *dynamic*.
Scheduled maintenance can either be:

- **Time-driven scheduled maintenance** is planned based on calendar time
- **Usage-based scheduled maintenance** is a usage parameter, expressed in for example driven kilometres or operating hours

Dynamic maintenance is divided in *usage severity based* and *load-based*, in both policies the maintenance interval will vary over time.

- **Usage-severity based dynamic maintenance** is a level more thorough than usage-based, this because usage-severity based not only takes the operating hours into account, but also considers the severity of the usage. Meaning the power settings are monitored in addition to the operating hours.
- **Load-based dynamic maintenance** is based on the actual load of the (sub)system, the actual relevant internal loads of a component are monitored.

Both usage-(severity)- and load-based maintenance require continuous monitoring of usage and/or load, and a physical model-based prognostic method to proactively predict the remaining useful life [4, 82, 88, 89].

In predictive maintenance, data (recommended operating hours or loads) provided by the manufacturer are compared to actual operating hours or loads to determine the maintenance moment. Depending on the type of (sub)system the actual loads can be counted, calculated or need to be monitored. However, to compare data with data provided by the manufacturer, it is not needed to collect several years of data to detect anomalies, solely real time monitoring is required. As the maintenance is performed before the failure occurs remaining useful life of the (sub)system is wasted. The costs of a predictive maintenance policy are low, slightly dependent on which kind of monitoring is required.

3.6. Suitable Maintenance Policies for Defined Problem

In the development of the maintenance cost model (MCM), different maintenance policies will result in different scenario's. For this research it is not feasible or desirable to include all maintenance policies scenario's. Therefore the most suitable and relevant maintenance policies need to be determined. First, a categorisation based on the required data per policy is made, whereafter the relevance of the different maintenance policies is evaluated.

3.6.1. Categorisation on the Basis of Required Data

Different maintenance policies require different data as input, dependent on, for example the level of monitoring. In table 3.1 the different policies are ranked based upon the required input per policy as explained in the previous sections, starting with the policy that requires the least data to be collected and analysed. In the second column of table 3.1, cost, represent the (implementation) cost of the different policies, not the cost of the maintenance itself. And in the last column, useful life, *yes* means that the maintenance is performed before failure and thus useful life of the (sub)system is wasted, and *no* means, no useful life is wasted.

Table 3.1: Maintenance Policies Categorised

Maintenance Policy	**Required Data**	**Cost**	**Useful Life**
Corrective	none	zero	no
Detective	none	zero	no
Opportunistic	none	zero	yes
Time-driven	recommendations from manufacturer	low	yes
Usage-based	recommendations from manufacturer	low	yes
Load-based	recommendations from manufacturer	low	yes
Usage-severity based	recommendations from manufacturer	medium	yes
Periodical Indirect	several years/recommendations from manufacturer	high/medium	yes
Continuous Indirect	several years/recommendations from manufacturer	high/medium	yes
Periodical Direct	several years	high	yes
Continuous Direct	several years	high	yes
Design Improvements	user experience	high	n/a

3.6.2. Relevance of Maintenance Policies for this Research

In the previous sections twelve different maintenance policies are explained, now it is key to determine which of these policies are most relevant to include in the MCM.

As can be seen in table 3.1, the four condition-based maintenance policies require several years of data, and besides that condition-based maintenance is a more expensive policy, of which the relative benefit decreases if the uncertainty in the failure threshold increases [19]. Therefore, it is logical to first determine with a cheaper method, predictive maintenance, for which (sub)system condition monitoring could be beneficial. This can be better visualised when looking at the standard deviation in figure 3.6. If a predictive maintenance policy results in a failure prediction with a low standard deviation (the blue line, in figure 3.6), it would be superfluous to apply the more expensive condition-monitoring to this (sub)system. However, if the failure prediction of a (sub)system results in a prediction with a high standard deviation (the green line, in figure 3.6), condition-monitoring of this (sub)system could result in a more accurate prediction and then be a worthwhile investment.

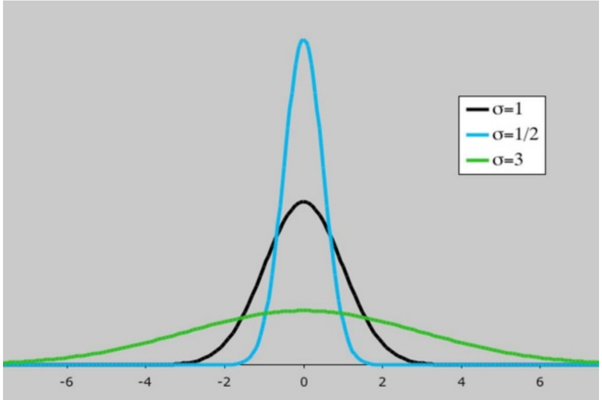


Figure 3.6: Normal Distribution with Same Mean and Different Standard Deviation

Since, a condition-based maintenance policy is more expensive than a predictive maintenance policy and at the moment of this research there is not several years of data available, condition-based maintenance policies will not be included in the MCM.

As explained in section 3.2 aggressive maintenance policies are outside the scope of this research.
Since detective maintenance policies are only applicable on protective devices, as elaborated upon in section 3.3, this maintenance policy is very limited in the choice of (sub)systems. As in this research it is desired to compare several maintenance policies for a (sub)system, including detective maintenance would restrict the choice of (sub)systems for this research considerably. Therefore, detective maintenance policies are at the current moment not considered interesting for this research, as these policies would limit the choice of (sub)systems without an added benefit.

Leaving corrective, opportunistic and predictive maintenance, as the policies suitable to be included in this research. Within predictive maintenance, there are *time-driven maintenance*, *usage-based maintenance*, *usage-severity based maintenance* and *load-based maintenance*. As explained in section 3.5.2 both usage-severity- and load-based maintenance require continuous monitoring of usage and/or load. By lack of research about maintenance in shipping, data and information from these type of monitoring systems (data collection or sensors) onboard a vessel is not available [84]. Therewith, usage-severity and load-based maintenance policies are not viable to be used in this research at this moment.

Thus, time-driven and usage-based remain as the two options of a predictive maintenance policy to be included in the MCM. As can be seen in table 3.1, the implementation costs of both policies are low. The difference in implementation costs between the two policies can be considered as minimal and therewith does not influence this consideration. Since implementation cost do not have a decisive influence, usage-based is considered the more relevant and interesting to include in this research, as this policy is based on actual operating hours (Mean-Time-To-Failure) [19, 82, 88] and thus a more dynamic policy than time-driven maintenance. Therefore, usage-based maintenance is the predictive maintenance policy that is included in this research.

Criticality of the (sub)system determines effectiveness of a policy [82]. Corrective maintenance is a relatively cheap policy, however the maintenance after failure and the corresponding down-time and off-hire costs can be very high. To be able to compare the effectiveness and costs of the different policies in the MCM, three maintenance scenario's for the different (sub)systems will be included, namely, corrective, opportunistic and usage-based predictive maintenance.

3.7. Summary

In this chapter different types of maintenance policies and their suitability to defined problem were analysed. Therewith in this chapter the answer to the third research question was presented:

> 3. *What are the maintenance policies currently applied in shipping, and which of these policies are suitable and relevant to include in this research?*

Based on the performed analysis, **corrective**, **opportunistic** and **usage-based predictive maintenance** are deemed the most suitable and relevant maintenance policies for this research, therefore these three policies are included in the MCM.

In the next chapter, chapter 4, first the knowledge gap in existing literature, based on the findings of this and the previous chapter, is identified. Whereafter, the theoretical basis of the MCM is explained.

4

Theoretical Basis of Maintenance Cost Model

Based on chapter 2 and chapter 3, conclusions can be drawn for the (un)available knowledge related to this study. The previous chapters illustrated that current approaches to determine total cost of an asset are incredibly diverse; a variety of generic total cost of ownership (TCO) and life cycle cost (LCC) concepts were discussed. No domain-specific TCO or LCC model was found in literature. Furthermore, the previous chapter illustrated that also the amount of maintenance policies currently available are incredibly diverse. Unfortunately, no literature about (cost) optimised maintenance in shipping was found. As a result, a new method to support cost optimised maintenance in shipping is required. Based on the above, the goal of this study, which is to model the maintenance costs of different maintenance policies, contributes in different fields of study.

Calculating the cost of a maintenance policy requires the prediction of failure behaviour of a system [29, 31, 77, 82, 94]. To predict or estimate failure behaviour of a system, performance data from the plant maintenance system (PMS), utilised by shipping management companies, is required. Making calculations based on practical data, with a huge range of parameters over a vast range of possible scenarios, involves solving several equations and considering interactions between the different systems. Therefore, a mathematical model calculating the maintenance cost of a system, for different scenario's and incorporation uncertainties is deemed the best solution to the defined problem. Concluding, the gap in the existing knowledge is, an accurate maintenance cost model for vessels, based upon/comparing several maintenance policies. The output is presented in such a way to support shipping management companies in strategic maintenance policy decision-making.

In this chapter the set-up and theory behind this Maintenance Cost Model (MCM) are explained. First, in section 4.1 the goal and set-up of the MCM are explained. Where after, in sections 4.2-4.7, the complete model is described, in five separate parts of the model. Concluding, in section 4.8 a summary of the findings in this chapter is provided.

4.1. Goal and Set-up of the Model

The goal of the maintenance cost model (MCM) is to be able to compare different maintenance policies, on the basis of the total cost of a policy over the (remaining) lifetime of a vessel.

An abstract representation of the MCM is presented in figure 4.1. As is illustrated in the figure, based on input data, first the mean-time-to-failure (MTTF) of the system or component is calculated. Whereafter, for each maintenance policy, the MTTF together with the other input data is used to calculate the cost of that policy. Finally, the previously calculated costs per policy are compared, where after a ranking of the maintenance policies is presented as outcome of the model.

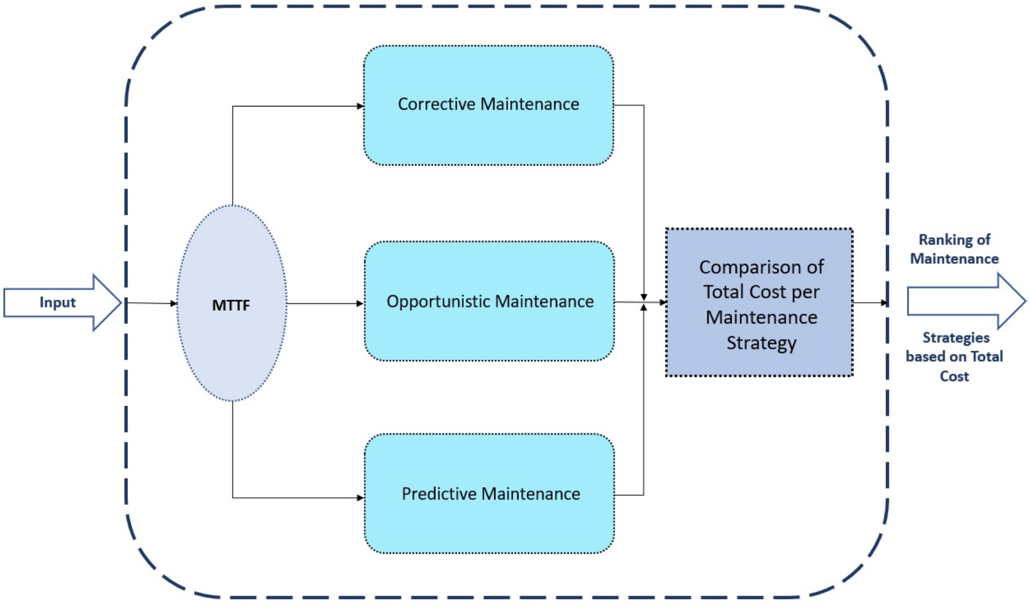


Figure 4.1: Abstract Representation of Maintenance Cost Model

As illustrated in figure 4.1 the cost calculations are performed separately for each maintenance policy. These maintenance policies are, as explained in chapter 3, *corrective*, *opportunistic* and *usage-based predictive maintenance*, hereafter *predictive maintenance*.

The delivery time of systems can be substantial [82, 84, 94], if this is the case this could often directly result in a proactive policy being optimal. Therefore, it is deemed interesting to investigate two separate tracks within the corrective maintenance policy. Namely, a corrective policy where the system or component is **ordered after breakdown** and a corrective policy with **one spare** system or component being stored, and thus being directly available. With this distinction being made within the corrective maintenance policy, there are by the MCM effectively four different policies compared:

- Corrective Maintenance - order on breakdown
- Corrective Maintenance - store 1 spare
- Opportunistic Maintenance
- Predictive Maintenance

When examining the model in figure 4.1, it can be seen that there are separate calculations per policy. In general the calculations per policy are the same. The same three main costs items are calculated for every policy, which together form the total cost per maintenance policy. The three main cost items are;

- Replacement cost
- Off-hire cost
- Reputation cost

The sum of these three cost items is the total cost of maintenance of that system or component, the over the lifetime of a vessel. As these calculations are largely similar for the four different policies, the explanation of the model is per main cost item. First explaining the general calculating per cost item, thereafter highlighting the (potential) differences per policy.

As is illustrated in figure 4.1 the mean-time-to-failure calculation is independent of the maintenance policy and this calculation is performed as the first step of the model. Therefore, the MTTF calculation is explained first, in section 4.2. Thereafter, the calculation of replacement cost, off-hire cost, and reputation cost are explained in sections 4.3, 4.4 and 4.3 respectively. Thereafter, in section 4.6 the total cost calculation, combining the three earlier calculated costs, is explained. Finally, in section 4.7, the last part of the model, the comparison between the policies, is elaborated upon. So, in the sections 4.2-4.7, the complete set-up of the MCM is explained.

4.2. Mean-Time-To-Failure Calculation

In this section the mean-time-to-failure (MTTF) calculations performed in the first part of the Maintenance Cost Model (MCM) are explained. Based upon the historic performance data from the planned maintenance system, utilised by shipping management companies, the MCM calculates the MTTF of every system or component.

To calculate the cost of a maintenance policy it is necessary to calculate the amount of times that repair or replacement is required over the lifetime of the vessel. To be able to calculate this amount, the prediction of failure behaviour of a system is required [29, 31, 82]. To predict the failure behaviour of a system, historic performance data is required [77, 82, 94]. In this research, the calculations of this statistical approach, incorporating failure times as the primary stochastic variable [88], will be made based on practical data, performance data from the plant maintenance system (PMS), utilised by shipping management companies. Based on this practical data the MTTF of every system or component can be calculated. How this calculation is performed is explained in the next two sections.

4.2.1. Theory behind MTTF Calculation

The two-parameter Weibull distribution is a failure rate description commonly used in reliability engineering [23, 25, 26, 44, 55, 77, 82, 92, 94]. This distribution is often used, because is has a correlation between the failure rate and time, and because this distribution allows for varying shape parameter. This varying shape parameter means that it is possible to describe both a decreasing, constant and increasing failure rate.

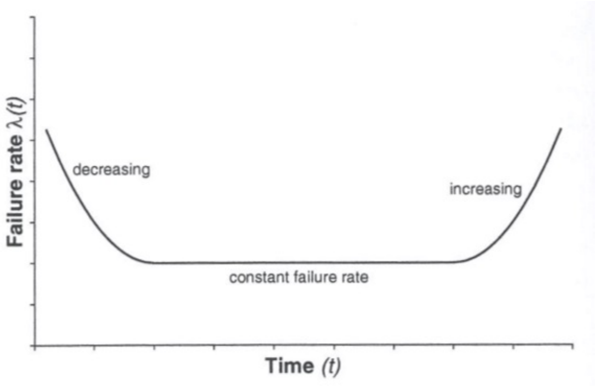


Figure 4.2: Bathtub Curve Showing Superposition of Decreasing, Constant and Increasing Failure Rate [82]

Illustrated in figure 4.2 is the bathtub curve, the combination (superposition) of a decreasing, constant and increasing failure rate. Since systems onboard a vessel are numerous and very diverse, it is possible that all three failure rates appear in this research. Since all failure rates can appear and it is valuable to know the failure rate of a system or component, it best suits this research to work with a theory that supports all three failure rates. Therefor, the Weibull distribution, as presented in equation 4.1, is deemed highly suitable for this research.

$$F(t) = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} e^{-(\frac{t}{\eta})^{\beta}} \tag{4.1}$$

In the probability density function of the Weibull distribution, as shown in equation 4.1, η is the scale parameter, which represents the characteristic life of the system or component, and β is the shape parameter, which indicates the failure behaviour. As mentioned before this varying shape parameter, β is one of the added values of the Weibull distributions, allowing to describe both a decreasing, constant and increasing failure rate. Concerning the value of this shape parameter, the value of β indicates in which phase of it's operational life a system or component is, see also figure 4.2 for further clarification.

- $\beta < 1$; means a **decreasing failure rate**, and this is phenomenon is often the result of *infant mortality or the burn-in phase* [26, 82]
- $\beta = 1$; means a **constant failure rate**, and describes *normal operational life or useful life phase* [26, 82]
- $\beta > 1$; means an **increasing failure rate**, and represents *ageing systems or the wear-out phase* [26, 82]

From the Weibull distribution, as shown in equation 4.1, the equation for the MTTF can be derived [77, 82, 94]. The MTTF equation derived from equation 4.1 then becomes;

$$MTTF = \eta * \Gamma\left(1 + \frac{1}{\beta}\right) \tag{4.2}$$

Based on the two equations, equation 4.1 and 4.2, and with the historic failure data, it is possible to determine, the MTTF and the failure probabilities.

4.2.2. Output MTTF Part of Model

Based on the historic failure data and with equations 4.1 and 4.2, in the first part of the model, the MTTF block, the following three things are calculated;

- MTTF
- Failure probabilities (5%, 10%, 15% ...- 95%)
- Beta

This is the output of the first block of the model, which will be used in the further calculations of the MCM. The MTTF and the set of failure probability outcome are presented in a table, giving the failure probabilities in steps of 5%. Based on literature [14, 22, 23, 28, 46, 77, 94], it is prudent to utilise a 90% failure probability, to determine the time-to-failure, for the two corrective maintenance policy calculations. For the other two maintenance policies, opportunistic and predictive, calculations for several different failure probabilities are made simultaneously, to be able to obtain the optimal (lowest cost) failure probability and corresponding interval between repairs.

Concluding, the output β is not utilised for any calculations in the model, β is direct output of the MCM. This as β is an indicator of the part of it's life a system is in. For users of the MCM, when determining a maintenance strategy it can be useful to know if a system is in the burn-in phase, normal operational life, or the wear-out phase.

As the first part of the MCM is explained, the calculations of the three different cost aspects are next. Starting with the replacement cost.

4.3. Replacement Cost Calculation

As explained in chapter 2, the replacement cost are the direct cost induced by maintenance. Replacement cost in this research refer to direct cost belonging to the replacement of a system or component. In general these cost consist of the:

- System price
- Man-hours of a service engineer
- Yard or quay cost
- Transportation (of the system) cost
- Port call cost
- Storage cost

Since there is a difference in the replacement cost calculation between the policies, now the calculation per policy is explained.

4.3.1. Replacement Cost - Corrective

As explained in chapter 3 when applying the corrective maintenance policy, no action is taken until after the failure of the system or component. For the corrective maintenance however, there are two separate scenarios calculated. The first based on the **order on breakdown** principle, meaning that there are no spares stored and also the ordering of the required system is done after the failure, resulting in the storage cost being zero for this policy. The second principle is the **store one spare** principle, meaning that there is always a spare system or component on stock in a warehouse or onboard. Meaning that replacement cost for this policy may be higher due to storage cost that are included.

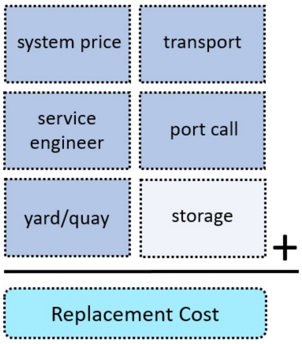


Figure 4.3: Abstract Representation of Corrective Replacement Cost Calculation

The replacement costs when applying a corrective policy consist of the system price, the man-hours of a service engineer, the yard or quay costs, storage cost, transportation cost and the port call cost, as illustrated in figure 4.3. The sole difference between the two previously explained scenarios, is in the storage cost.

4.3.2. Replacement Cost - Opportunistic

As explained in chapter 3, opportunistic maintenance, is a proactive maintenance policy. Meaning that action is taken before a failure of the system or component occurs. In the shipping industry a very apparent opportunity presents itself with the compulsory 2,5 year class survey.

The replacement cost in an opportunistic policy consist of the system price, the man-hours of a service engineer, and the transportation cost, as illustrated in figure 4.4.

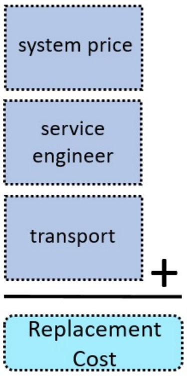


Figure 4.4: Abstract Representation of Opportunistic Replacement Cost Calculation

In comparison with corrective maintenance the yard/quay cost and the port call cost are excluded, as these costs are a result of the class survey and are not evoked by the repair or replacement of this system or component. Furthermore, storage cost are not included as planned maintenance (every 2,5 year, is quite planned) provides an excellent opportunity for ordering the systems or components just in time, eliminating the requirement for storage. Resulting in opportunistic maintenance replacement cost consisting of the system price, the man-hours of a service engineer and the transportation cost of the system.

4.3.3. Replacement Cost - Predictive

As explained in chapter 3, predictive maintenance, is a proactive maintenance policy. Meaning that action is taken before a failure of the system or component occurs. In this research an optimisation is performed to find the optimal moment to perform maintenance before failure, based on 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, and 90% failure probability.

The predictive maintenance policy, replacement costs are based upon the system price, the man-hours of a service engineer, yard/quay cost, port call cost and the transportation cost, as illustrated in figure 4.5.

In comparison with the already explained corrective and opportunistic maintenance cost calculations. The replacement cost include yard/quay and port call cost, as these cost are a direct result of the repair. However, storage cost are not included as scheduled maintenance provides an excellent opportunity for ordering the systems or components just in time, eliminating the requirement for storage. Resulting in predictive maintenance replacement cost consisting of the system price, the man-hours of a service engineer, yard/quay cost, port call cost and the transportation cost of the system.

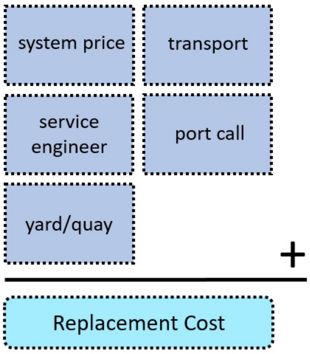


Figure 4.5: Abstract Representation of Predictive Replacement Cost Calculation

Following this explanation of the replacement cost calculation, next is an explanation of the difference in probability of a failure occurring between a corrective and proactive policy.

4.3.4. Probability Difference Corrective versus Proactive

There is a difference in the probability of a failure occurring, between the corrective and proactive policies. When applying a corrective policy, action is only taken after a failure occurs, thus the probability of a failure is in that case 100%. Thus, for a corrective policy the replacement costs are, 100% times the replacement cost calculation as illustrated in figure 4.3, resulting in equation 4.3.

$$Replacement\ Cost_{corrective} = Replacement\ Cost_{corrective} * 100\% \tag{4.3}$$

When calculating the costs of a proactive policy, the failure probability must also be included in the calculation. Thus, for every failure probability, the costs are separately calculated. Resulting in nine different costs per failure, being calculated for the two proactive maintenance policies, illustrated in table 4.1.

Table 4.1: Probability Cost Calculation - Example

Probability	**Cost per Probability**
10%	150,-
20%	300,-
30%	450,-
40%	600,-
50%	750,-
60%	900,-
70%	1050,-
80%	1200,-
90%	1350,-

Including the failure probability in the calculation, does not mean simply multiplying the costs with the different probabilities. As, even with a 10% failure probability, there always remains the change of an unforeseen break-down or failure, before the scheduled proactive maintenance, thus how does this calculation work?

Taking this 10% failure probability, as a calculation example. With a 10% failure probability, there is a 10% chance of a failure occurring before the scheduled maintenance, and therewith a 90% chance that no failure occurs before the scheduled maintenance.

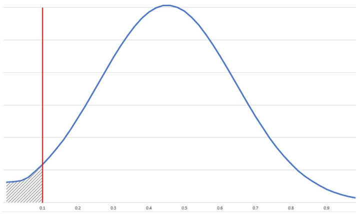


Figure 4.6: Failure Probability Density Function - 10% Highlighted in Grey

For further clarification, this is also illustrated in figures 4.6 and 4.7, the red line is, in both graphs, at the 10% failure probability, the chosen maintenance moment in this case. The grey shaded area below the probability density function and left of the red line, in figure 4.6, represents the chance of a failure occurring before maintenance. The green shaded area, in figure 4.7, to the right of the red line, and underneath the probability density function, represents the chance of a failure happening after the maintenance, thus in this case not happening.

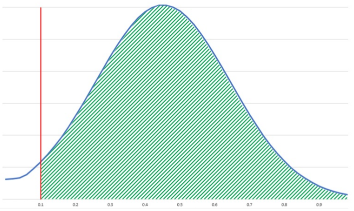


Figure 4.7: Failure Probability Density Function - 90% Highlighted in Green

So, whenever there is a chance of a failure happening, there is also always the reversed chance of that failure not occurring. More explicit:

10% chance at **Failure** ↔ **90%** chance at **No Failure**

When maintenance is performed before the failure occurs it is considered proactive, however when a failure happens before the scheduled maintenance, it falls in the corrective maintenance policy. Meaning that, in the 10% calculation example, there is a 90% chance of the calculated cost of the proactive maintenance policy happening, and a 10% chance of the cost of the corrective - *order on breakdown* maintenance policy happening. Thus, in equation-form this results in the replacement cost per failure probability, being calculated as illustrated in equation 4.4:

$$Cost_{probability\,n} = ((1-n) * cost_{proactive\,policy}) + (n * cost_{corrective\,policy}) \tag{4.4}$$

Where n stands for the nine different probabilities, which are calculated. Resulting in the following replacement cost calculation, of a fictive system, for the 10% example:

Corrective Replacement Cost	**Proactive Replacement Cost**
3000,-	1500,-

$$Replacement\,Cost_{probability\,0.1} = ((1-0.1) * 1500,-) + (0.1 * 3000,-))$$

$$Replacement\,Cost_{probability\,0.1} = (0.9 * 1500,-) + (0.1 * 3000,-)$$

$$Replacement\,Cost_{probability\,0.1} = 1650,-$$

Concluding, with equation 4.4 for both the opportunistic and the predictive maintenance policies, nine, for the nine different probabilities, separate replacement costs are calculated. Thus, the total outcome of the replacement costs for the three separate maintenance policy calculations, in the MCM, is now as follows:

- Corrective - *order on breakdown* Replacement Cost
- Corrective - *store 1 spare* Replacement Cost
- Opportunistic Replacement Cost
  - 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80% & 90%
- Predictive Replacement Cost
  - 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80% & 90%

This difference in probability is the case for all three cost aspects, for the two proactive policies. Thus, also nine separate off-hire costs and nine separate reputation costs are calculated. As now all the replacement cost calculations have been explained, next the off-hire cost calculation is explained.

4.4. Off-hire Cost Calculation

As explained in chapter 2, the off-hire costs are part of the indirect cost induced by maintenance. Off-hire cost in this research refer to cost induced by the downtime of the vessel. Meaning that downtime of the system has a direct operational impact on the vessel. Off-hire cost in general in this research refer to loss of income due to the vessel not being 100% operational, due to the replacement of a system or component. The off-hire cost are based upon **downtime** [hours] of the vessel times the **income/hour** [€/hour] times the **percentage of the cargo** that the vessel can not transport due to the downtime, as illustrated in figure 4.8.

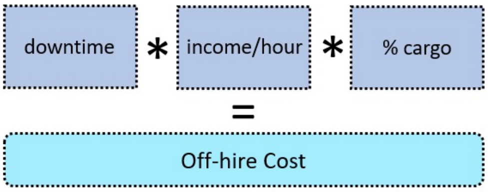


Figure 4.8: Abstract Representation of Off-hire Cost Calculation

To explain these three concepts a little further:

- **Downtime** : in hours, time the vessel is not fully operational due to the failure
- **Income/hour** : in €/hour, the income per hour that is lost due to the failure
- **% cargo** : in %, some failures cause the vessel to carry less cargo (e.g. when one MYCOM compressor fails, the total cooling capacity decreases, thus the tanks of a gas carrier are only allowed to be filled for 85% with ethylene, thus there is a 15% cargo loss, due to this failure)

Since there is a difference in the off-hire cost calculation between the policies, now the calculation per policy is explained.

4.4.1. Off-hire Cost - Corrective

For the corrective maintenance policy, there are two separate scenarios calculated. The first based on the **order on breakdown** principle, the second principle is the **store one spare** principle. In both scenarios the off-hire cost are calculated as explained above and illustrated in figure 4.8. The difference between the two scenarios is the length of the downtime. In the order on breakdown principle the downtime can be longer, as this is influenced by the delivery time of the system.

The downtime is the repair time added up with either the delivery time of the system or the time the vessel takes to sail to the repair location, whichever of these two is longer, the longest of the two determines the critical path, as shown in figure 4.9. Between the two different scenario's within the corrective policy the downtime can differ, as the delivery time from a manufacturer can be significantly longer, than from a storage location.

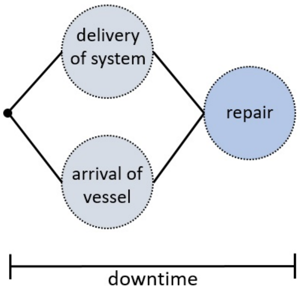


Figure 4.9: Critical Path determination of Corrective Downtime

4.4.2. Off-hire Cost - Opportunistic

The off-hire cost when applying an opportunistic maintenance policy are calculated as explained above and illustrated in figure 4.8. The difference between the corrective and the opportunistic policies is only visible in the length of the downtime. This difference in downtime exists for two reasons.

First, when a repair or replacement is known in advance, the system or component can be ordered in time, in general eliminating the delivery time and therewith decreasing downtime, normally resulting in lower off-hire cost. Thus, in the determination of the critical path for downtime in opportunistic maintenance, the delivery time is excluded, as there is enough time to order the component in advance.

Second, in opportunistic maintenance there is only downtime (for a single system or component), when the repair time of that system, exceeds the time required for the class survey. As the initial ”downtime” is a result of the class survey and not evoked by the repair or replacement of the system or component.

Meaning that in opportunistic maintenance the downtime is determined by a comparison of the time required for the class survey and the repair time only, as illustrated in figure 4.10.

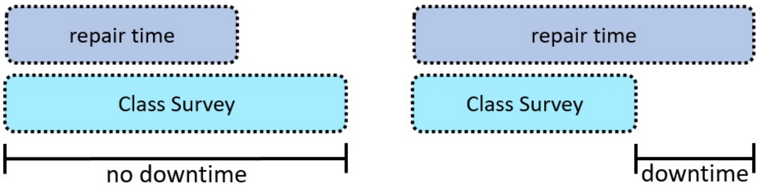


Figure 4.10: Opportunistic Downtime Determination

4.4.3. Off-hire Cost - Predictive

The off-hire cost when applying a predictive maintenance policy are calculated as explained above and illustrated in figure 4.8. The difference between the corrective or opportunistic and the predictive policy is only visible in the length of the downtime. When a repair or replacement is known in advance, the system or component can be ordered in time, in general eliminating the delivery time and therewith decreasing downtime, normally resulting in lower off-hire cost.

In predictive maintenance the downtime equals the repair time, as is illustrated in figure 4.11. The delivery time and the time required for the vessel to sail to a location are not included in the calculation. As the repair or replacement is known in advance, the system or component can be ordered in time, eliminating the delivery time. And as the repair or replacement is known in advance, it can be scheduled in agreement with the vessel operator, together finding the most suitable moment with the lowest downtime.

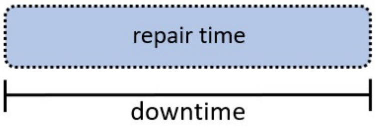


Figure 4.11: Predictive Downtime Determination

Finally, as the differences between the off-hire calculations for all three policies are explained. The last aspect of the off-hire calculation is, as mentioned before, the different probabilities. For both the opportunistic and the predictive maintenance policies, nine, for the nine different probabilities, separate off-hire costs are calculated, based on equation 4.4. Thus, the total outcome of the off-hire costs for the three separate maintenance policy calculations, in the MCM, is now as follows:

- Corrective - *order on breakdown* Off-hire Cost
- Corrective - *store 1 spare* Off-hire Cost
- Opportunistic Off-hire Cost
  - 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80% & 90%
- Predictive Off-hire Cost
  - 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80% & 90%

As now all aspects of the off-hire cost calculation have been explained, next, the reputation cost calculation is explained.

4.5. Reputation Cost Calculation

Reputation cost in this research refer to the second indirect cost, resulting from the short term effect of a failure of a system or component. As explained in chapter 2 loss of reputation, loss of hire, loss of a long-term time-charter and even rejection from an oil major are the risks of unforeseen maintenance. Also explained in chapter 2, is the difference between long term reputation damage and short term reputation costs, as also that the latter is included in the MCM and the former is not. Short term reputation costs, are the reputation costs directly induced by a failure on that vessel.

In the reputation cost calculation, all possible vetting risk options are quantified based upon historic data. As explained in chapter 2, this calculation is based on the requirement of a condition of class (CoC). When a CoC is invoked by a failure, there are, in general, four possible consequences;

- No consequence
- No sailing until failure has been repaired
- No sailing for 3 months
- No sailing for 6 months

First, the cost per consequence is calculated. When there is no consequence, the reputation loss is considered nil, therefore these costs are zero. For the other three possible consequences, the costs are calculated by multiplying the time the vessel is banned with the off-hire rate utilised by the shipping company, illustrated in table 4.2.

Table 4.2: Cost per Consequence

Consequence	**Cost per Consequence**
no consequence	zero
no sailing until failure has been repaired	off-hire rate * downtime
no sailing for 3 months	off-hire rate * 3 months
no sailing for 6 months	off-hire rate * 6 months

When evaluating the calculation of the cost per consequence, there might appear to be a slight overlap with the off-hire costs. As in both calculations there is counted with the downtime of the vessel. Where in the off-hire cost calculation, the actual cost belonging to the downtime of the vessel are calculated, the downtime is used as an input to calculate short term reputation costs. However, the timing of a ban from a client is, not (always) simultaneous to the timing of the failure and downtime, therefore there is no doubling of cost.

To illustrate, only when a vessel is proposed, by the chartering department to a client for a certain cargo, only then a potential client screens a vessel. Meaning in practice, the vessel is at the time of the failure transporting cargo for a client that does not object, so the vessel can continue her business. Where after she is proposed for a new cargo and then a potential client screens the vessel. Meaning it is possible that although, the repair has already been done, the repair is scheduled for next month, and/or the client does not agree with the measures taken, thus therefore the client rejects the vessel for a certain period (e.g. three months). This can happen if they see there is still, or use to be a damage, or the shipping management can not explain what it did to prevent it from happening again. The client then request answers (about e.g. preventive measurements, or a root cause analysis) and a good inspection. So, for the next three months the client does not give any business, thus the shipping management company has three months to provide the answers.

Summarising, this means that, independent of the repair-time, based on the condition of the vessel, it is possible to receive a ban. Which does not mean the vessel is out of operation completely, but since it is not possible to sail for certain clients, it is not possible to get the best cargo on the market. Meaning the vessel might has to transport cargo that generates less income, or might has to sail ballast, to be able to pick up cargo at a terminal that has not banned the vessel. So, as a ban is only imposed as soon as a vessel is applied for certain business, which might be after the actual repair, there is no doubling with the off-hire cost calculation. Furthermore, it is clear that the short term reputation cost are dependable of numerous uncertainties. The short term reputation cost calculation, developed for the MCM, is an accurate simplification of the more complex real world.

Next, after the cost per consequence have been calculated. Based upon historic data, the probability of a consequence appearing is determined. Thereafter, the cost per consequence is multiplied with the probability of the consequence appearing, resulting in an average cost per failure.

Finally, the **average cost per failure** is multiplied with the **probability this failure occurs** and a **severity factor**. An abstract representation of this calculation, of the reputation cost, is presented in figures 4.12 and 4.13.

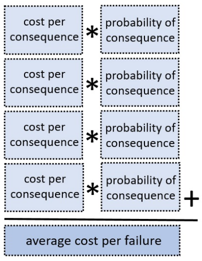


Figure 4.12: Average Cost per Failure Calculation

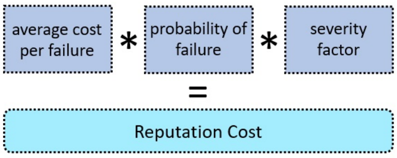


Figure 4.13: Abstract Representation of Reputation Cost Calculation

Only the severity factor has not yet been explained. This is a factor that can vary between 0 and 1, where one obviously results in the highest possible reputation cost and zero results in the reputation cost being zero. With this factor a weight is given to the existing vetting risk of a failure. It is, for example, possible that the reputation costs of a certain failure are higher, when a long term contract with an oil major gets rejected, compared to the reputation costs of the same failure occurring during a voyage charter for another client. The severity factor allows for a distinction in the impact of the vetting risk on the reputation cost. The severity factors are company specific and depend on the vetting risk and the type of contract in combination with the type of client. Meaning that any company, when first utilising the MCM, needs to determine and fill in the severity factors. In table 4.3, this interdependence between vetting risk, contract and client is illustrated.

Table 4.3: Severity Factors

Vetting Risk	**Client**	**Contract**	**Factor**
Yes	Oil Major	Time Charter	0-1
Yes	Oil Major	Voyage Charter	0-1
Yes	Other Client	Time Charter	0-1
Yes	Other Client	Voyage Charter	0-1
Yes	No Client	No Contract	0-1
No	Oil Major	Time Charter	0-1
No	Oil Major	Voyage Charter	0-1
No	Other Client	Time Charter	0-1
No	Other Client	Voyage Charter	0-1
No	No Client	No Contract	0-1

Since there are differences in the reputation cost calculations between the different policies, now the calculation per policy is explained and the differences are highlighted.

4.5.1. Reputation Cost - Corrective

For the corrective maintenance policy, there are two separate scenarios calculated. The first based on the **order on breakdown** principle, the second principle is the **store one spare** principle. In both scenarios the reputation cost are calculated as explained above, with a probability of the failure occurring of 90%, and illustrated in figure 4.13.

Between the two different scenarios within the corrective maintenance policy the reputation costs are calculated in the same manner. However, the total reputation cost can be different for the two policies, due to a difference in downtime. The downtime can be different, as the delivery time of the system can different, as explained.

This difference in downtime directly affects the reputation cost, as the downtime is multiplied with the off-hire rate to calculate the cost per consequence, for the second consequence, as can be seen in table 4.2.

4.5.2. Reputation Cost - Opportunistic

The reputation cost when applying an opportunistic maintenance policy are calculated as explained before and illustrated in figure 4.13. The difference between the corrective and the opportunistic policies is visible in the length of the downtime. This difference in downtime exists for two reasons, as explained above in section 4.4.2.

Furthermore, the reputation cost are in general expected to be lower, as foreseen maintenance during a class survey does not normally induce a vetting risk, therewith minimising the reputation cost.

4.5.3. Reputation Cost - Predictive

The reputation cost when applying a predictive maintenance policy are calculated as explained above and illustrated in figure 4.13. The difference between a corrective or opportunistic and the predictive policy is only visible in the length of the downtime. When a repair or replacement is known in advance, the system or component can be ordered in time, in general eliminating the delivery time and the time required for the vessel to sail to a repair-location, therewith decreasing downtime, normally resulting in lower reputation cost.

Furthermore, also the reputation consequences are in general expected to be less severe, as foreseen maintenance can be scheduled in agreement with the vessel operator, together finding the most suitable moment with the lowest operational impact, therewith minimising the reputation cost.

Finally, as the differences between the reputation calculations for all three policies are explained. The last aspect of the reputation cost calculation is, as mentioned before, the different probabilities. For both the opportunistic and the predictive maintenance policies, nine, for the nine different probabilities, separate reputation costs are calculated, based on equation 4.4. Thus, the total outcome of the reputation costs for the three separate maintenance policy calculations, in the MCM, is now as follows:

- Corrective - *order on breakdown* Reputation Cost
- Corrective - *store 1 spare* Reputation Cost
- Opportunistic Reputation Cost
  - 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80% & 90%
- Predictive Reputation Cost
  - 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80% & 90%

As now all aspects of the reputation cost calculation have been explained, next, the total cost calculation is explained.

4.6. Total Cost Calculation

Finally, when the replacement cost, off-hire cost, and reputation cost per failure are determined, the sum of these three separate costs results in the total cost per failure, as illustrated in figure 4.14.

The final part of the calculation is determining the amount of failures and the moment in time of these failures, over the remaining lifetime of the vessel. As there is a difference in the calculation between the policies, now the calculation is explained separately for the corrective and the proactive policies.

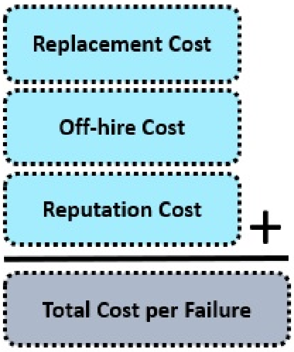


Figure 4.14: Total Cost per Failure Calculation

4.6.1. Total Cost - Corrective

In both scenarios the total cost are calculated as explained above, with a probability of the failure occurring of 90% [14, 22, 23, 28, 46, 77, 94], as explained in section 4.2. Between the two different scenarios within the corrective maintenance policy the total costs are calculated the same.

This calculation based upon the earlier calculated 90%-time-to-failure combined with the downtime, resulting in a mean-time-between-failures (MTBF). With the MTBF and the remaining lifetime of the vessel, it is possible to determine how many failures, thus replacements, there will be and when. This is illustrated in equation 4.5:

$$Number\,of\,Replacements\; = \frac{Remaining\,Lifetime\,of\,Vessel}{MTBF} \tag{4.5}$$

When the amount of replacements is determined, the amount of replacement times the total cost per failure, gives the total maintenance cost of that system over the lifetime of the vessel. This is illustrated in equation 4.6:

$$Total\,Cost\; = Number\,of\,Replacements\, *\, Total\,Cost\,per\,Failure \tag{4.6}$$

Finally, these total costs are corrected, calculating the current value of the future cost. For this calculation the company specific weighted average cost of capital (WACC) and the inflation rate are utilised [5, 16, 41, 47, 65, 67]. This is illustrated in equation 4.7:

$$Present\,Value\,Total\,Cost\; = \frac{Total\,Cost * Inflation\,Rate^{\,years}}{WACC^{\,years}} \tag{4.7}$$

Concluding, from the corrective maintenance calculation the result is, two separate total costs, one for the *”order on breakdown”* scenario and a second for the *”store one spare”* scenario. These two total costs are later compared with the total costs of the opportunistic maintenance and the predictive maintenance calculations.

4.6.2. Total Cost - Opportunistic & Predictive

When the replacement cost, off-hire cost, and reputation cost per failure are determined, the sum of these separate costs results in the total cost per failure, as illustrated in figure 4.14. The total cost calculation for an opportunistic and a predictive policy are identical, and therefore explained together in this section.

As explained in the preceding sections, when calculating the cost of opportunistic and predictive, together proactive, maintenance policies, the complete set of failure probabilities is utilised. A separate calculation at 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80% and 90% is performed to find the optimal (lowest cost) moment to perform maintenance before failure. Therewith determining, the optimal coinciding failure rate, and the best time-to-failure. This optimisation means that for all failure probabilities, 10%-90%, the costs are calculated separately and then finally in the last phase, the lowest total cost is determined, providing the optimal failure probability. An example total cost calculation is presented in table 4.4.

Table 4.4: Total Cost Calculation - Example

Probability	**Replacements**	**Replacement Cost**	**Off-hire Cost**	**Reputation Cost**	**Total Cost per Probability**
10%	10	1500,-	1000,-	1000,-	35.000,-
20%	8	1600,-	1500,-	1200,-	34.400,-
30%	8	1700,-	2000,-	1400,-	40.800,-
40%	8	1800,-	2500,-	1600,-	47.200,-
50%	6	1900,-	3000,-	1800,-	40.200,-
60%	6	2000,-	3500,-	2000,-	45.000,-
70%	6	2100,-	4000,-	2200,-	49.800,-
80%	4	2200,-	4500,-	2400,-	36.400,-
90%	4	2300,-	5000,-	2600,-	39.600,-

As illustrated in table 4.4 by the green colour, the 20% failure probability corresponds with the lowest total costs. However, it can also be seen in table 4.4, that the lowest total costs, does not necessarily mean the lowest replacement, off-hire or reputation costs, as the total cost are also depended on the number of replacements. First, as illustrated in figure 4.14, the three separate costs are added up, resulting in a total cost per failure probability.

Thereafter, this total cost per failure probability is multiplied with the corresponding amount of replacements. This number of replacements is different for the different failure probabilities, as can be seen in the second column in table 4.4. This because different failure probabilities, have a different time-to-failure. The number of replacements is determined, as in the corrective policy, by dividing the remaining lifetime of the vessel by the MTBF (the time-to-failure plus the downtime), illustrated in equation 4.8:

$$Number\ of\ Replacements = \frac{Remaining\ Lifetime\ of\ Vessel}{MTBF} \tag{4.8}$$

As the number of replacements (column 2, table 4.4) and the summation of the costs are now known, the total cost per probability can now be calculated. A multiplication of the two gives the total cost per probability over the lifetime of the vessel, the last column of table 4.4. This multiplication is illustrated in equation 4.9:

$$Total\,Cost\,per\,Probability = Number\,of\,Replacements * Total\,Cost\,per\,Failure \quad (4.9)$$

Finally, these total costs are corrected, calculating the current value of the future cost. For this calculation the company specific weighted average cost of capital (WACC) and the inflation rate are utilised [5, 16, 41, 47, 65, 67]. Based on the total costs per probability, last column of table 4.4, the optimal (lowest total cost) failure probability can now be determined. Thus, from both the opportunistic and the predictive maintenance calculations the result is, one final total cost.

Concluding, with an overview of the entire model, figure 4.15. When examining the MCM in more detail, now the MTTF, corrective, opportunistic and predictive maintenance calculations have been completed.

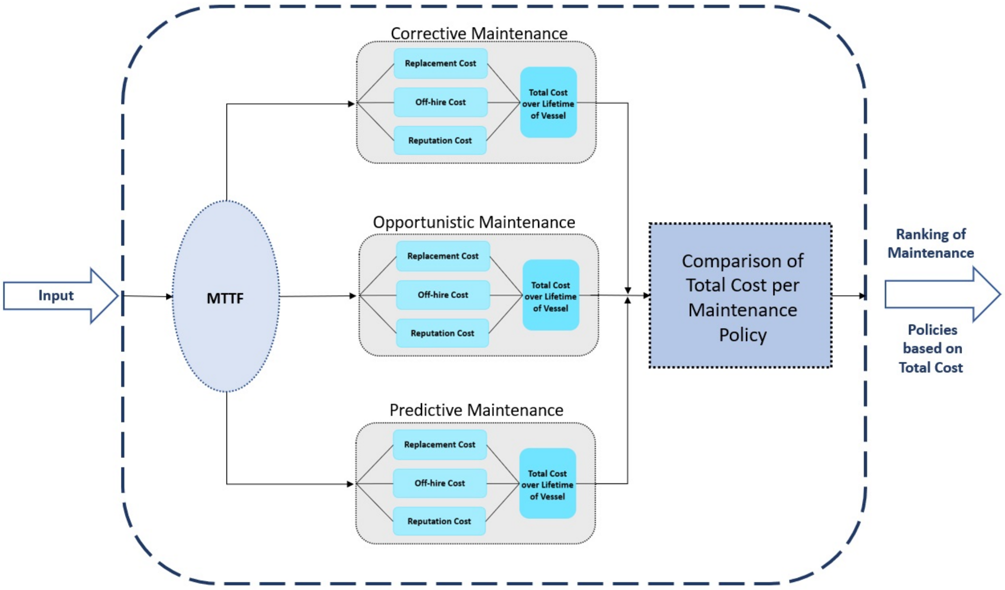


Figure 4.15: Overview of Maintenance Cost Model

At this stage of the calculations within the MCM, there are four total cost figures calculated:

- Corrective Maintenance Policy Cost - *order on breakdown*
- Corrective Maintenance Policy Cost - *store 1 spare*
- Opportunistic Maintenance Policy Cost
- Predictive Maintenance Policy Cost

Therefore, the only step that remains is to compare these total costs, and determine the optimal policy. This is the next and last phase of the MCM, where the total costs are compared with the other total costs of the different maintenance policies. This last part of the MCM is explained in the next section.

4.7. Comparison of Total Cost per Maintenance Policy

In sections 4.3, 4.4, 4.5, and 4.6 the cost calculations of the different maintenance policies are explained. The result of these calculations is four total cost figures, two for corrective, one for opportunistic and one for preventive. Therefore, the only step that remains is to compare these total costs.

In the last part of the Maintenance Cost Model (MCM) the four calculated total costs are compared and ranked, lowest to highest. As lower costs are desirable for any commercial company. This ranking, showing the four policies, as illustrated in table 4.5, is output of the MCM.

Table 4.5: Maintenance Policies Ranking - Example

Policy	**Cost**	**Replacements**	**Every**	**Failure Probability**
Opportunistic Maintenance	€200.000,-	9	2.5 years	37%
Predictive Maintenance	€400.000,-	50	0.5 years	10%
Corrective Maintenance - *o.o.b.d.*	€600.000,-	3	8 years	100%
Corrective Maintenance - *s.1.s.*	€800.000,-	3	8 years	100%

As can be seen in table 4.5, next to the ranking of the four policies, more information is presented. Per policy the following information is included in the ranking:

- Corresponding total cost over the lifetime of the vessel
- Number of replacements over the lifetime of the vessel
- Replacement interval
- Failure probability

The calculation of the total cost over the lifetime of the vessel has been explained in section 4.6. In that same section 4.6, equation 4.5 calculates, the number of replacements over the lifetime of the vessel. The replacement interval is determined by the calculated time-to-failure of a policy, explained in section 4.2. As also the calculation of the failure probability has been explained in section 4.2.

Based on this ranking of the four maintenance policies, illustrated in table 4.5, shipping companies can make a better substantiated maintenance policy decision per separate system or component, based on the total cost per policy.

These are the conditions and assumptions, important to realise and keep in mind, when evaluating a policy ranking.

- The MCM is not developed to make a decision, only to help substantiate the decision-making process. It is imperative to **critically evaluate the results** of the MCM, as there is still a substantial level of uncertainty (depending on the uncertainty of the input values, the error bands). Thus, the policy ranking outcome should not be leading, there is another level of decision-making required, that looks at more than just the numbers.

- Corrective Maintenance - *o.o.b.d.* - stands for the corrective **order on breakdown** policy

- Corrective Maintenance - *s.1.s.* - stands for the corrective **store 1 spare** policy

- The **predictive maintenance** policy has a possible **failure probability** varying between, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, and 90%.
- The **failure probability** of the **opportunistic maintenance** policy is the probability corresponding with the failure probability at the time of the compulsory class survey. Thus this failure probability can vary between 1% and 99%.
- Both **corrective maintenance** policies always have a **failure probability** of 100%, as it is the nature of the policy to take action after the failure occurs.
- To determine the **time-to-failure** of a **corrective policy** there is calculated with the 90% failure rate, because when calculating with the 100%, outliers could trouble the data-set [22, 77, 82, 94].
- Therefore, it is possible that one of the proactive policies has the **same number of replacements**, and thus the same replacement interval, only a different failure probability. As it is not possible to say with 100% certainty a failure will occur, the maximum failure probability of the proactive policies is 99%.
- Furthermore, the time-to-failure and therewith number of replacements of the corrective policy are assumed at the 90% failure rate, as explained in section 4.2. Calculating with this high percentage, leads to a **relatively low number of replacements**. As it is likely that there are more replacements, as it is likely that systems break down earlier. Another option is the calculate the number of replacements and the replacement interval of the corrective maintenance policy based on the MTTF. In table 4.6, the number of replacements and the replacement interval are calculated based on the MTTF.

Table 4.6: Maintenance Policies Ranking - Example II

Policy	**Cost**	**Replacements**	**Every**	**Failure Probability**
Opportunistic	€200.000,-	9	2.5 years	37%
Predictive	€400.000,-	50	0.5 years	10%
Corrective - *o.o.b.d.*	€1.200.000,-	6	4 years	100%
Corrective - *s.1.s.*	€1.600.000,-	6	4 years	100%

An unmistakable effect of calculating with the MTTF, is the increase in total cost of the two corrective policies. In this particular example resulting in a more substantial difference between the four policies, however not influencing the ranking.

It is plausible that, there are situations where calculating the corrective policies, based on the MTTF instead of the 90% failure rate, has an influence on the ranking and the optimal policy.

Calculating the number of replacements of the corrective policies with the MTTF, leads to complexity when comparing with the proactive policies. As the proactive policies calculate the total cost based on a varying failure probability, the likelihood that there are more replacements also varies. When evaluating table 4.6, the likelihood that there will be more replacements in the predictive policy is relatively small, 10%. In the opportunistic policy, slightly bigger, 37%, but still acceptable. However, it is also possible that the probabilities of one of these (or both) policies is higher, even above the MTTF. So, the complexity in comparing then arises, when do you stop calculating with the ”real” probability, and switch to the, maybe more realistic in terms of likelihood of replacements, MTTF?

To approach a more realistic likelihood of replacements for all four policies, a suggestion for further research could be to simulate (e.g. Monte Carlo Simulation) for a certain time-period the values, based upon the reciprocal distribution that has been estimated. When simulating, the observed variation can be better quantified and several scenarios can be tested, and labelled as optimistic and pessimistic. When the simulation is run often enough for several different cases, (i.e. Monte Carlo), the boundaries of the different cases can be established.

In the continuation of this thesis and thus in generating the results, the 90% time-to-failure, and thus the corresponding amount of replacements, are used in the calculation of the corrective maintenance policy. Meaning that the obtained results, especially as the failure probability increases, are optimistic. The (corrective) total costs are optimistically determined, based on a relatively low number of replacements, with a high likelihood of more replacements, thus assuming a best case scenario.

4.8. Summary

In the previous chapters a gap in existing knowledge is established, to fill this gap, a novel method to support cost optimised maintenance in shipping is required. A mathematical model, calculating the maintenance cost of a system, for different scenario’s and incorporation uncertainties, is deemed a solution to defined problem. Therewith also answering the fourth research question:

> *4. What could be a method to be able to calculate and compare the total cost per maintenance policy?*

This chapter presents a method, the Maintenance Cost Model, to integrate actual behaviour data from a vessel in the maintenance cost estimation. The actual data from the vessels is used to determine the failure behaviour of the systems onboard. This failure behaviour is used to calculate the actual failure rate and mean-time-to-failure. Based on this actual data, the replacement-, off-hire, and reputation cost are calculated. Combined resulting in different total cost per maintenance policy per system. The Maintenance Cost Model generates a ranking of the maintenance policies, based on lowest cost. The outcome of the Maintenance Cost Model, the policy ranking, can be used by shipping management companies, to obtain a better substantiated system specific maintenance policy.

As in this chapter the theory of the maintenance cost model is explained, in the next chapter, chapter 5, the model will be implemented and verified.

5

Implementation & Verification

In the previous chapter the theoretical background of the Maintenance Cost Model MCM is explained. Based on this theory the next step implementing and verifying the MCM, which is explained in this chapter. First, the implementation is explained in section 5.1. After the implementation, the MCM is verified to behave as expected, this verification is presented in section 5.2. Finally, this chapter is concluded with a summary in section 5.3.

5.1. Implementation Maintenance Cost Model

In this section about the implementation of the MCM, first the choice of software is explained, thereafter the input and the output of the model are elaborated upon. Starting with the software choice.

5.1.1. MCM Software

The Maintenance Cost Model (MCM) is developed for the shipping industry in general and for shipping management companies in specific. The MCM needs to be suitable to be used by a diverse group of professionals, such as a;

- Vessel Manager
- Superintendent
- Asset Manager
- Maintenance Engineer
- Fleet Manager
- Technical Director
- COO
- CFO

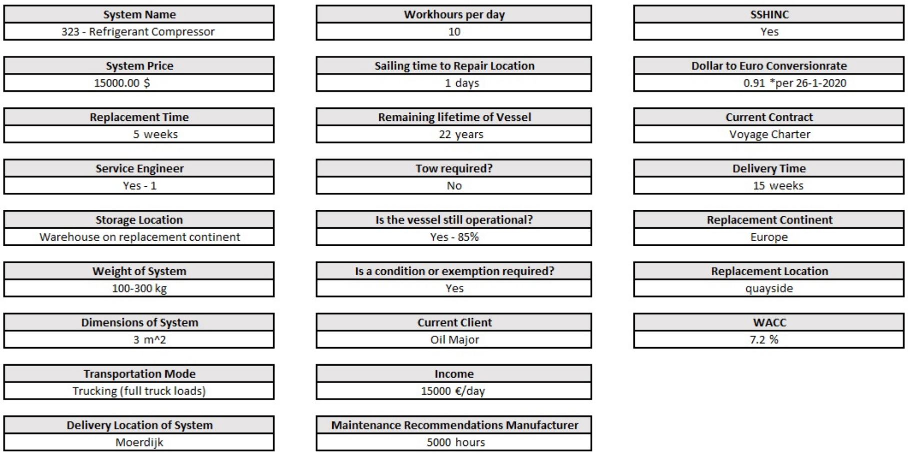
Due to the diverse background and educational attainment of the intended user-group of the MCM, in combination with the fact, that it is not common for shipping management companies to have access to extensive numerical computing programs, it is decided to built the model in Microsoft Excel.

5.1.2. Input MCM

As explained a diverse user-group should be able to use the MCM, therefore the required input of the model is kept as basic as possible and the manner of input is basic and intuitive. For the MCM to calculate to total cost of a maintenance strategy it is necessary to have certain information about the system or component and about the vessel and it's operating area. The following information, and what it is used to calculate for, is asked in the input screen of the MCM;

- Name of the System
- Price of the System → Replacement Cost
- Repair Time → Downtime
- Service Engineer required → Replacement Cost
- Storage Location → Storage Cost
- Weight of System → Storage Cost
- Dimensions of System → Storage Cost
- Transportation Mode of System → Transportation Cost
- Remaining Lifetime of Vessel → Number of failures/repairs
- Is the Vessel still Operational → Downtime
- Vetting Risk due to Failure → Reputation Cost
- Current Client → Reputation Cost
- Income → Off-hire Cost & Reputation Cost
- Current Contract → Reputation Cost
- Delivery Time → Downtime
- Replacement Continent → Replacement Cost
- Replacement Location → Replacement Cost
- Weighted Average Cost of Capital → Current Value of Total Cost
- Inflation Rate → Current Value of Total Cost

As this is a lot of information and could potentially lead to a lot of unusable input data, almost all information is to be given within a predefined format, a drop down menu, leaving no room for own interpretation of the required information. An abstract print screen of the input page is shown in figure 5.1.



System Name	323 - Refrigerant Compressor
System Price	15000.00 $
Replacement Time	5 weeks
Service Engineer	Yes - 1
Storage Location	Warehouse on replacement continent
Weight of System	100-300 kg
Dimensions of System	3 m^2
Transportation Mode	Trucking (full truck loads)
Delivery Location of System	Moerdijk
Workhours per day	10
Sailing time to Repair Location	1 days
Remaining lifetime of Vessel	22 years
Tow required?	No
Is the vessel still operational?	Yes - 85%
Is a condition or exemption required?	Yes
Current Client	Oil Major
Income	15000 €/day
Maintenance Recommendations Manufacturer	5000 hours
SSHINC	Yes
Dollar to Euro Conversionrate	0.91 *per 26-1-2020
Current Contract	Voyage Charter
Delivery Time	15 weeks
Replacement Continent	Europe
Replacement Location	quayside
WACC	7.2 %

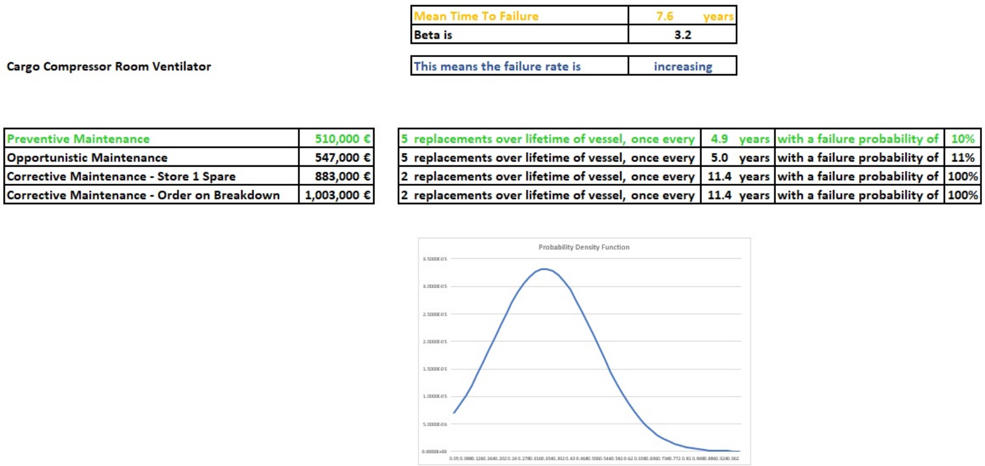
Figure 5.1: Print Screen of the Input Page of the MCM

Besides these system and vessel specific information, also the historic failure data from the Plant Maintenance System (PMS) is required as input to calculate the failure rates and times. This information is not asked in the "front" input page, but there is a second "Data Input" page. In this page the historic failure data can be pasted, after being exported from the PMS.

5.1.3. Output MCM

The output of the MCM is a ranking of the four maintenance policies. This ranking, shows the four policies and their total cost over the lifetime of the vessel for the system or component. The policies are ranked lowest to highest based on total cost, with the lowest displayed in green. As explained in chapter 4, next to the ranking of the four policies, more information is presented. Per policy also the number of replacements over the lifetime of the vessel, the replacement interval, and the corresponding failure probability are displayed.

On the output screen are, next to this ranking of the four maintenance policies, also displayed the probability density function of the failure rate and the calculated mean-time-to-failure (MTTF) and β. This extra information is not required for the ranking of the policies, but might aid in making a better substantiated maintenance policy decision and are therefore included as output of the model. An abstract print screen of the output page is shown in figure 5.2.



Mean Time To Failure	7.6 years
Beta is	3.2

Cargo Compressor Room Ventilator

This means the failure rate is	increasing

Preventive Maintenance	510,000 €	5 replacements over lifetime of vessel, once every	4.9 years	with a failure probability of	10%
Opportunistic Maintenance	547,000 €	5 replacements over lifetime of vessel, once every	5.0 years	with a failure probability of	11%
Corrective Maintenance - Store 1 Spare	883,000 €	2 replacements over lifetime of vessel, once every	11.4 years	with a failure probability of	100%
Corrective Maintenance - Order on Breakdown	1,003,000 €	2 replacements over lifetime of vessel, once every	11.4 years	with a failure probability of	100%

Figure 5.2: Print Screen of the Output Page of the MCM

5.2. Verification Maintenance Cost Model

After implementation of the MCM, it is important to verify that the model calculates what it is expected to calculate. This verification is performed in small steps, verifying individual parts of the model, these steps and their expected and obtained outcome are presented in table 5.1.

Table 5.1: Verification Process

Description	Expected Outcome	Obtained Outcome	Result
Total Cost depend on all three separate costs	- Increase only replacement cost - Decrease only off-hire cost - Increase only reputation cost	- Total cost increased - Total cost decreased - Total cost increased	✓ ✓ ✓
Values check	Values are correct	Values were correct	✓
Corrective -*store 1 spare* policy is independent of delivery time	Total cost of corrective-*s1s* remain the same	Total cost of corrective-*s1s* remained the same	✓
Change **Remaining lifetime of Vessel** from 25 years to 5 years	- Total cost decrease - Number of replacements decrease	- Total cost decreased - Number of replacements decreased	✓ ✓
Check **combination** of no current client and current contract time charter	- This combination is not possible, the calculation of the severity factor should give an error	- Severity Factor results in error	✓
Change **WACC** from 5% to 10%	Total cost decrease	Total cost decreased	✓
Change **Inflation** from 3% to 8%	Total cost increase	Total cost increased	✓
Increase the MTTF	- Three separate cost items don't change - Total cost increase - Number of replacements increase	- Three separate cost items didn't change - Total cost increased - Number of replacements increased	✓ ✓
Failures without operational impact, only result in replacement cost	- Off-hire cost = €0,- - Reputation cost = €0,-	- Off-hire cost = €0,- - Reputation cost = €0,-	✓ ✓
Failures with operational impact, result in all 3 costs	- Replacement cost ≠€0,- - Off-hire cost ≠€0,- - Reputation cost ≠€0,-	- Replacement cost ≠€0,- - Off-hire cost ≠€0,- - Reputation cost ≠€0,-	✓ ✓ ✓

In table 5.1 not all steps and their expected and obtained outcome are presented. When evaluating the table it can be seen that the fourth, fifth, sixth and seventh verification step are printed in bold. These are four of the individual input variables of the MCM that are altered, while keeping all the other input variables constant. For readability, not all 25 tests are individually presented here. The verification of the complete set of input variables of the MCM, is included in appendix B.

5.3. Summary

In the previous chapter, a mathematical model, calculating and comparing maintenance cost of different policies, is presented.

In this chapter the implementation of the model, in Microsoft Excel, is explained. The required input of the model is elaborated upon and the output screen is presented. Furthermore, the calculations performed by the model are separately verified. After this successful implementation and verification of the model, in the next chapter, chapter 6, the first application of the model will be described.

6

Application of MCM : Anthony Veder

After the development of the Maintenance Cost Model (MCM), the MCM is applied to calculate the maintenance cost for a diverse group of systems that are onboard the gas tankers of shipping management company, Anthony Veder. In this chapter the findings of this first application of the MCM, a case study, are presented.

First, in section 6.1 the chosen systems are described. Second, in section 6.2 the outcome per system is presented. Following, the results are evaluated in section 6.3. Thereafter, different techniques to determine failure behaviour for Anthony Veder are compared in section 6.4. Furthermore, in section 6.5 a roadmap for further implementation of the MCM within Anthony Veder is presented. Finally, in section 6.6 this chapter is concluded with a summary.

6.1. Systems Used for Validation

It is important to test all boundaries and find potential limitations of the MCM, however not feasible within the time-frame of this research to run all systems onboard through the model. As the focus of this research is on the systems and engines, a division of systems onboard, into balanced test-groups is made. This system decomposition is presented in figure 6.1.

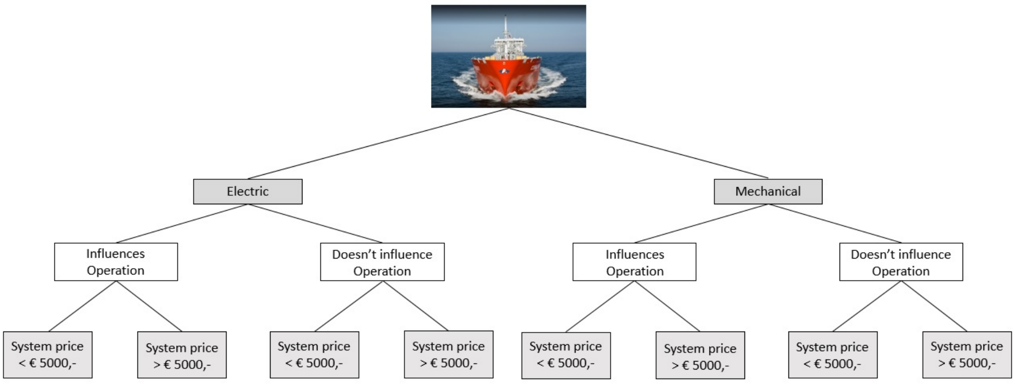


Figure 6.1: System Decomposition for MCM

As explained in chapter 3, **electric** and **mechanical** systems in general have different failure behaviour. Therefore this is the first distinction made, dividing the systems and engines, into two general groups, as visible in figure 6.1.

Thereafter, the effect, of a failure of a system, on the **operation** is the next distinction. A failure can cause that a vessel is no longer (fully) operational. Also, as explained in chapter 4, a failure can impose a vetting risk, while the vessel is still sailing. As not being operational or imposing a vetting risk, affect the downtime, off-hire and reputation cost, thus negatively affect the possibility to generate income. In this distinction, these two consequences of a failure are seen together. Again dividing the systems in two groups, based on the effect a failure has on the possibility to generate income. Summarising, either a failure of a system has no operational impact and imposes no vetting risk, **OR**, a failure of a system has operational impact and/or imposes a vetting risk. This is the second distinction made, now creating four general groups of systems.

Finally, the **system price** is chosen to be the last distinctive factor. A purchase price boundary of €5000,- is chosen, as this is the company specific boundary until which the people directly involved with vessel maintenance have signing authority, any cost above need to be approved by higher management. With this last distinction the existing four groups are again divided in two, resulting in eight groups.

The system decomposition, as explained, creates a general division of eight groups. In collaboration with the asset manager and maintenance engineer of Anthony Veder, a system belonging in each group is selected. Sometimes the available information about certain systems is minimal and as the information proved insufficient to perform the research, a different system representing the same group is chosen. The selected systems and the group they represent are presented in table 6.1. In the next section, an explanation of each system is included.

Table 6.1: Selected Systems

Group #	**Electric**	**Mechanical**	**Influences Operation - Yes**	**Influences Operation - No**	**price < €5000,-**	**price > €5000,-**	**System**
Group I	•		•		•		Magnetron X-band
Group II	•		•			•	X-band Radar
Group III	•			•		•	ECDIS
Group IV	•			•	•		GPS
Group V		•	•			•	MYCOM Compressor
Group VI		•	•		•		Cargo Compressor Room Ventilator
Group VII		•		•	•		HVAC Air Handling Unit
Group VIII		•		•		•	Lube Oil Transfer Pump

As the systems are selected, all information is now inserted in the MCM. The results from this application of the model and an explanation of the different systems, is presented in the next section.

6.2. Results Application MCM

In this section the results of the application of the MCM are presented per group (system), resulting in 8 separate sections, in the same order as presented in table 6.1. The failure behaviour is calculated based on the historic data from BASSnet, the vessel Planned Maintenance System (PMS) Database utilised by Anthony Veder.

To allow comparison of the results of the eight groups, all vessel specific input information is kept the same, only the system specific input is varied between the eight groups. The lifetime of the vessel has been determined at 25 years, the economic lifetime of a gas tanker. Operational area is Europe and the delivery and storage location of the system have been set in Rotterdam. All this input can be varied at a later stage, when further applying the MCM to a specific vessel, however for the comparison in this research only system specific variations are made.

6.2.1. Group I - Magnetron X-band Radar

The first system is the magnetron of the X-band radar. This is critical bridge-equipment that is required to be onboard and functioning. Failure of the magnetron directly results in a vetting risk, thus a failure of the of the magnetron influences operation. In table 6.2, the system specific input of the x-band magnetron is presented.

Table 6.2: Input Variables - Magnetron X-band Radar

Price	€1500,-	**Delivery time**	1 hour
Influences Operation	Yes	**Repair time**	2 hours
Service Engineer	Yes	**10% Failure**	2500 hours
MTTF	10000 hours	**90% Failure**	17.250 hours

The ranking of the four maintenance policies formed by the MCM, for the magnetron of the X-band radar is presented in table 6.3.

Table 6.3: Maintenance Policies Ranking - Magnetron X-band Radar

Policy	**Cost**	**Replacements**	**Every**	**Failure Probability**
Opportunistic Maintenance	€4.824.000,-	9	2.5 year	99%
Predictive Maintenance	€6.108.000,-	61	0.4 years	10%
Corrective Maintenance - *o.o.b.d.*	€6.157.000,-	12	2 years	100%
Corrective Maintenance - *s.1.s.*	€6.162.000,-	12	2 years	100%

As can be seen in table 6.3 for the magnetron of the X-band radar an opportunistic maintenance policy is recommended based on the total cost. However, based on the assumptions and limitations, as explained in chapter 4, next to this outcome, there is another level of decision-making involved.

- With a duration of 2.5 years, the failure rate is 99%, while with 2 years it is 100%, this may feel counter-intuitive. However it is correct, as explained in chapter 4. In short, both corrective maintenance policies always have a failure probability of 100%, as it is the nature of the policy to take action after the failure occurs. In the opportunistic policy the 2,5 year class survey is the first opportunity. As the mean-time-to-failure (MTTF) of an X-band magnetron is 1.2 year, this first opportunity is well after. The 90% failure probability is at 2 years, so the first opportunity has an even higher probability. Since it is not certain the magnetron has failed after 2,5 years, in a proactive policy the failure probability is never 100%. Thus, 99% is the highest probability for a proactive policy in this research.

- In the optimal predictive strategy the magnetron is replaced every 0,4 year, the failure rate is low, 10%, thus there is a relatively higher level of certainty. This strategy is more expensive due to the relatively high (namely 61) number of replacements over the lifetime of the vessel. Maybe, evaluating the intermediate results, provides a more suitable option, not replacing it every 0,4 years, while maintaining a certain level of certainty in the failure probability. The intermediate results of the MCM are presented in table 6.4.

Table 6.4: Intermediate Outcome - Magnetron X-band Radar

Policy	**TTF**[1]	**Replacement**		**Repl.**	**Off-hire**	**Repu.**	**Total**[2]	**Failure**
		Interval	**#**	**Cost**	**Cost**	**Cost**	**Cost**	**Prob.**
Corr. *oobd*	1.97	2 year	12	1800	16250	807500	6.157.000	100%
Corr. *s1s*	1.97	2 year	12	7000	16250	807500	6.162.000	100%
Opp.	0.4	2.5 year	9	1800	16250	807500	4.824.000	99%
	0.6	2.5 year	9	1800	16250	807500	4.824.000	99%
	0.8	2.5 year	9	1800	16250	807500	4.824.000	99%
	1.0	2.5 year	9	1800	16250	807500	4.824.000	99%
	1.2	2.5 year	9	1800	16250	807500	4.824.000	99%
	1.4	2.5 year	9	1800	16250	807500	4.824.000	99%
	1.6	2.5 year	9	1800	16250	807500	4.824.000	99%
	1.8	2.5 year	9	1800	16250	807500	4.824.000	99%
	2.0	2.5 year	9	1800	16250	807500	4.824.000	99%
Pred.	0.4	0.4 year	61	1733	3087	152857	6.108.000	10%
	0.6	0.6 year	42	1740	4550	289688	7.894.000	20%
	0.8	0.8 year	31	1748	6013	410493	8.234.000	30%
	1.0	1 year	25	1755	7475	515270	8.327.000	40%
	1.2	1.2 year	20	1762	8938	604023	7.807.000	50%
	1.4	1.4 year	17	1770	10400	676750	7.437.000	60%
	1.6	1.6 year	15	1778	11863	733451	7.116.000	70%
	1.8	1.8 year	13	1785	13325	774125	6.516.000	80%
	2.0	2 year	12	1793	14788	798773	6.213.000	90%

- Based on the intermediate results, in table 6.4, it is obvious that choosing the opportunistic maintenance policy has a big change of surprises in hindsight. As for all nine different times-to-failure, the 2,5 year class survey is the first opportunity, in all cases resulting in a total of nine replacements over the lifetime with a 99% change of more replacements. As the separate costs are equal to a corrective policy, the low total costs are a direct result of the low number of replacements.

---

[1] Time-To-Failure in years

[2] The Total Cost are lower than the three separate costs added up and multiplied with the number of replacements. This, as the total costs are corrected, representing the current value of future investments.

- When comparing the 10% and the 90% failure probability of the predictive policy, there is almost no difference in the total cost, however a big difference in the certainty of these costs. Therefor, the predictive policy replacing every 0.4 year could be a suggestion, based on the calculations of the MCM.

- My personal suggestion would be to further investigate the failure behaviour data. As replacing a system every 0.4 years, seems unwanted and unrealistic. This means replacing it every three months, if this is really the case it might be worth changing supplier. However, it is also possible that the data-set is troubled. That the MTTF, 10000 hours, is calculated based on varying input from the vessels, some on operating hours and others on calendar time. This is worth investigating as 10000 operating hours seem more logical MTTF than one year.

- Investing in a system, where the operating hours can be logged, and determining the predictive maintenance policy based on operating hours would be my advice. The delivery and repair time are short, therefore it seems a system very suitable to be proactively replaced before failure, as this is a system that when failed imposes a vetting risk.

When comparing the recommended 10% predictive policy with the corrective policies, the total costs are considered equal. However, the difference in certainty of the calculations is substantial. As, explained in chapter 4, with a 90% failure rate, these are optimistic corrective costs. With a 10% failure rate, these are realistic predictive costs. Thus, in pursuing a best substantiated cost estimate, based solely on table 6.3, and without further research, a predictive policy is recommended. The small difference between the predictive and the corrective policies, is largely due to the fact that the system price and therewith replacement costs are almost negligible. Waiting until the system fails means increasing the reputation cost associated with failure of the X-band. For Anthony Veder, there is an improvement in total cost for the maintenance budget of the magnetron of the X-band radar of at least 1% per vessel, when comparing the recommended policy with the policy currently applied.

6.2.2. Group II - X-band Radar

The second system is the complete X-band radar, as explained in section 6.2.1, the X-band is critical bridge-equipment that is required to be onboard and functioning. Therefore, failure of the radar directly influences operation of the vessel. In table 6.5, the system specific input of the x-band is presented.

Table 6.5: Input Variables - X-band Radar

Price	€14000,-	**Delivery time**	1.5 days
Influences Operation	Yes	**Repair time**	1 day
Service Engineer	Yes	**10% Failure**	0.1 years
MTTF	3.2 years	**90% Failure**	5.5 years

The ranking of the four maintenance policies formed by the MCM, for the X-band radar is presented in table 6.6.

Table 6.6: Maintenance Policies Ranking - X-band Radar

Policy	**Cost**	**Replacements**	**Every**	**Failure Probability**
Predictive Maintenance	€2.009.000,-	4	5.5 years	90%
Corrective Maintenance - *s.1.s.*	€2.029.000,-	4	5.5 years	100%
Corrective Maintenance - *o.o.b.d.*	€2.036.000,-	4	5.5 years	100%
Opportunistic Maintenance	€2.111.000,-	4	5 year	81%

Based on the total cost per policy as presented in table 6.6, for the entire X-band radar a predictive maintenance policy is recommended. However, all total costs are basically the same, and all recommended failure rates are relatively high, which is unwanted for a system that influences the operation. So, it is necessary to further evaluate the proactive policies. The intermediate results of the proactive policies, are presented in table 6.7.

Again in this case, the failure probabilities may feel counter-intuitive. However, as explained in chapter 4, both corrective maintenance policies always have a failure probability of 100%, as it is the nature of the policy to take action after the failure occurs. But are calculated with the 90%-time-to-failure, to prevent the influence from outliers troubling the data-set. The 90%-time-to-failure is 5.5 years. Resulting in the same replacement interval, for corrective and predictive, with different failure probabilities. Now let's evaluate the intermediate results of the proactive policies, table 6.7.

Table 6.7: Intermediate Outcome - Magnetron X-band Radar

Policy	**TTF**	**Replacement**		**Repl. Cost**	**Off-hire Cost**	**Repu. Cost**	**Total Cost**	**Failure Prob.**
		Interval	**#**					
Opp.	0.46	2.5 year	9	15256	12330	526939	3.215.000	41%
	1.06	2.5 year	9	15256	12330	526939	3.215.000	41%
	1.66	2.5 year	9	15256	12330	526939	3.215.000	41%
	2.26	2.5 year	9	15256	12330	526939	3.215.000	41%
	2.98	2.5 year	9	15256	12330	526939	3.215.000	41%
	3.58	2.5 year	9	15256	12330	526939	3.215.000	41%
	4.18	5 year	4	15285	243000	779738	2.111.000	81%
	4.9	5 year	4	15285	243000	779738	2.111.000	81%
	5.5	5 year	4	15285	243000	779738	2.111.000	81%
Pred.	0.46	0.5 year	53	15233	4913	153188	5.466.000	10%
	1.06	1.1 year	23	15240	7700	290346	4.287.000	20%
	1.66	1.7 year	14	15248	10488	411473	3.642.000	30%
	2.26	2.3 year	10	15255	13275	516571	3.243.000	40%
	2.98	3 year	8	15263	16063	605638	3.032.000	50%
	3.58	3.6 year	6	15270	18850	678675	2.545.000	60%
	4.18	4.2 year	5	15278	21638	735682	2.298.000	70%
	4.9	4.9 year	5	15285	24425	776658	2.429.000	80%
	5.5	5.5 year	4	15293	27212	801605	2.009.000	90%

As the repair time is only one day, it may not be necessary to plan this replacement during the 2,5 year class survey. It is plausible that other opportunities present itself, where it is possible to replace the entire X-band, without downtime of the vessel. Since this is a system that influences the operation of the vessel, a proactive policy with a relatively low failure probability seems wisest. The specific proactive maintenance choice, thus the decision which costs are acceptable against which probability, is beyond the scope of this research.

6.2.3. Group III - ECDIS

The third system is the ECDIS (Electronic Chart Display Information System), ECDIS is non critical bridge-equipment, as it is allowed to navigate with hard-copy nautical charts. Therefore, failure of ECDIS does not directly influence the operation. In table 6.8, the system specific input of the ECDIS is presented.

Table 6.8: Input Variables - ECDIS

Price	€10.000,-	**Delivery time**	2 weeks
Influences Operation	No	**Repair time**	2 days
Service Engineer	Yes	**10% Failure**	1.6 years
MTTF	5.4 years	**90% Failure**	8.3 years

The ranking of the four maintenance policies formed by the MCM, for ECDIS is presented in table 6.9.

Table 6.9: Maintenance Policies Ranking - ECDIS

Policy	**Cost**	**Replacements**	**Every**	**Failure Probability**
Predictive Maintenance	€38.700,-	3	6.6 years	70%
Opportunistic Maintenance	€38.900,-	3	7.5 year	79%
Corrective Maintenance - *o.o.b.d.*	€40.000,-	3	8.3 year	100%
Corrective Maintenance - *s.1.s.*	€53.000,-	3	8.3 year	100%

Based on the total cost per policy as presented in table 6.9, for ECDIS a predictive maintenance policy is recommended. Replacing it every 6.6 years, meaning three times over the lifetime of the vessel, with a failure probability of 70%. This is a relatively high failure probability, so all total costs observed in table 6.9 are on the optimistic side, however as failure of this system does not directly influence the operation, a high failure probability is acceptable. As long as the user is aware that the total costs, with a high failure probability, represent an optimistic scenario. For Anthony Veder, there is an improvement in total cost for the maintenance budget of the magnetron of the ECDIS of 3% per vessel, when comparing the recommended policy with the policy currently applied.

6.2.4. Group IV - GPS

The fourth system is the GPS (Global Positioning System), GPS is critical bridge-equipment, however as all vessels from Anthony Veder have two GPSes on the bridge, a failure of one GPS does, in this research, not directly result in a vetting risk. In table 6.10, the system specific input of the GPS is presented.

Table 6.10: Input Variables - GPS

Price	€3000,-	**Delivery time**	2 days
Influences Operation	No	**Repair time**	1 day
Service Engineer	No	**10% Failure**	6.0 years
MTTF	10.8 years	**90% Failure**	15.2 years

The ranking of the four maintenance policies formed by the MCM, for GPS is presented in table 6.11.

Table 6.11: Maintenance Policies Ranking - GPS

Policy	**Cost**	**Replacements**	**Every**	**Failure Probability**
Corrective Maintenance - *o.o.b.d.*	€1800,-	1	15.2 year	100%
Opportunistic Maintenance	€1800,-	1	15 years	89%
Predictive Maintenance	€1900,-	1	13 years	70%
Corrective Maintenance - *s.1.s.*	€8000,-	1	15.2 year	100%

Based on the total cost per policy as presented in table 6.11, only corrective - *store 1 spare* for the GPS can be written off. Storage of the GPS is certainly not beneficial, due to the short delivery time compared with the long storage time. The MCM does at this moment not even take into account that storing a system like a GPS is for a period of 15 years is not desirable as a GPS becomes outdated long before that period.

Regarding the other three policies, based on the total costs, no recommendation can be made, as the costs are all basically the same. However, when further evaluating the results, a corrective maintenance policy is recommended. The mean-time-to-failure (MTTF) of the GPS is 10.8 years. The recommended corrective policy replaces the GPS every 15.2 years, with a high risk of failure before this moment, so the total costs are optimistic. However, as a failure does not influence the operation and the system has a short delivery and repair time, a corrective policy is best as no useful life of the system is wasted, because action is only taken after a failure.

When it is not desirable to calculate the operational budget with the optimistic outcome (€1800,-), it is also an option to calculate with the MTTF, 10.8 years, based here upon 2 replacements are more likely. Thus, resulting in a rough estimate of €3600,- over the lifetime of the vessel. Either-way, the corrective -*o.o.b.d.* policy is recommended for the GPS. When comparing the recommended policy with the policy currently applied by Anthony Veder, there is no improvement in total cost for the maintenance budget of the GPS per vessel, as the recommended policy is the currently applied policy.

6.2.5. Group V - MYCOM Compressor

The fifth system is the MYCOM (MAYEKAWA Refrigerant Compressor), this refrigerant compressor is critical equipment to keep the cargo cooled. The MYCOM is critical equipment, however as all vessels from Anthony Veder have more then one MYCOM, failure of a MYCOM does not directly result in the vessel not being operational. However, with the failure of a MYCOM, cooling capacity is lost, therefore the tanks can only be loaded for 85% of their capacity. Thus, failure of a MYCOM has a direct impact on the operation. In table 6.12, the system specific input of a MYCOM is presented.

Table 6.12: Input Variables - MYCOM Compressor

Price	€70.000,-	**Delivery time**	9 months
Influences Operation	Yes	**Repair time**	2 days
Service Engineer	Yes	**10% Failure**	12.125 hours
MTTF	47.625 hours	**90% Failure**	101.500 hours

The ranking of the four maintenance policies formed by the MCM, for a MYCOM is presented in table 6.13.

Table 6.13: Maintenance Policies Ranking - MYCOM Compressor

Policy	**Cost**	**Replacements**	**Every**	**Failure Probability**
Corrective Maintenance - *s.1.s.*	€984.000,-	2	11.6 year	100%
Predictive Maintenance	€3.079.000,-	2	9.1 years	70%
Opportunistic Maintenance	€3.107.000,-	2	10 year	77%
Corrective Maintenance - *o.o.b.d.*	€3.310.000,-	2	11.6 year	100%

Based on the total cost per policy as presented in table 6.13, for the MYCOM a corrective maintenance policy, with storage of a spare MYCOM, is recommended. Even with a failure probability of 100%, thus likely that the MYCOM will fail before the (foreseen) replacement. As the MYCOM is an expensive system, wasting useful life does not compete with the downtime induced by repair only, when there is a spare system stored. Furthermore, the low off-hire and reputation costs, when eliminating the delivery time, make this policy cheaper than replacing the MYCOM proactively.

The mean-time-to-failure (MTTF) of a MYCOM is 6.1 years, so when calculating the number of replacements based on the MTTF, approximately 4 replacements, lead to a total cost of roughly €3.900.000,-. This is a less optimistic, more realistic number, see the explanation in chapter 4. However, as all failure probabilities in table 6.13 are relatively high, and there is a significant difference between the cost of a corrective policy and the other policies, this does not influence the policy ranking. For Anthony Veder, there is an improvement in total cost for the maintenance budget of the MYCOM of 70% per vessel, when comparing the recommended policy with the policy currently applied.

6.2.6. Group VI - Cargo Compressor Room Ventilator

The sixth system is the cargo compressor room ventilator, this ventilator is critical equipment to keep the cargo room free of any toxic or flammable cargo vapour. Therefore, failure of a cargo compressor room ventilator directly results in a vetting risk. In table 6.14, the system specific input of a cargo compressor room ventilator is presented.

Table 6.14: Input Variables - Cargo Compressor Room Ventilator

Price	€5000,-	**Delivery time**	1 week
Influences Operation	Yes	**Repair time**	2 days
Service Engineer	No	**10% Failure**	4.4 years
MTTF	7.6 years	**90% Failure**	11.4 years

The ranking of the four maintenance policies formed by the MCM, for a cargo compressor room ventilator is presented in table 6.15.

Table 6.15: Maintenance Policies Ranking - Cargo Compressor Room Ventilator

Policy	**Cost**	**Replacements**	**Every**	**Failure Probability**
Predictive Maintenance	€510.000,-	5	4.9 years	10%
Opportunistic Maintenance	€547.000,-	5	5 year	11%
Corrective Maintenance - *s.1.s.*	€883.000,-	2	11.4 years	100%
Corrective Maintenance - *o.o.b.d.*	€1.003.000,-	2	11.4 years	100%

Based on the total cost per policy as presented in table 6.15, the recommended maintenance policy for the cargo compressor room ventilator is proactive. The difference between the predictive and opportunistic policies is negligible, both between €500.000,- and €550.000,-, both after five years and both with a failure probability around 10%. The mean-time-to-failure (MTTF) of a cargo compressor room ventilator is 7.6 years. In the proactive maintenance policies the ventilator is replaced 5 times over the lifetime of a vessel, meaning roughly every 5 years. If the decision is made to perform this replacement during the dry dock, downtime can be eliminated, however the failure probability slightly increases. As in this outcome of the MCM the two recommended policies have a low failure probability, thus a higher level of certainty. These total costs are more realistic than the optimistic total costs of the corrective maintenance policies. When comparing the recommended policies with the policy currently applied by Anthony Veder, there is an improvement in total cost for the maintenance budget of the cargo compressor room ventilator of 49% per vessel.

6.2.7. Group VII - HVAC Air Handling Unit

The seventh system is the air handling unit of the HVAC (Heating Ventilation Air Conditioning) of the accommodation. The air handling unit is the device used to regulate and circulate air in the accommodation, this is not a system that is critical for operation and failure of this system does not result in a vetting risk. In table 6.16, the system specific input of an air handling unit is presented.

Table 6.16: Input Variables - HVAC Air Handling Unit

Price	€25.000,-	**Delivery time**	6 months
Vetting Risk	No	**Repair time**	4 days
Service Engineer	Yes - 3	**10% Failure**	7.6 years
MTTF	15 years	**90% Failure**	20.6 years

The ranking of the four maintenance policies formed by the MCM, for air handling unit is presented in table 6.17.

Table 6.17: Maintenance Policies Ranking - HVAC Air Handling Unit

Policy	**Cost**	**Replacements**	**Every**	**Failure Probability**
Corrective Maintenance - *o.o.b.d.*	€16.000,-	1	20.8 years	100%
Opportunistic Maintenance	€21.000,-	1	15 year	53%
Predictive Maintenance	€23.000,-	1	12.9 years	40%
Corrective Maintenance - *s.1.s.*	€45.000,-	1	20.8 years	100%

Based on the total cost per policy as presented in table 6.17, for the air handling unit (AHU) a corrective maintenance policy is recommended. The mean-time-to-failure (MTTF) of the AHU is 14.5 years. The recommended corrective policy replaces the AHU after 20.8 years, with a high risk of failure before this moment. Due to the low reputation cost taking this risk is cheaper than replacing the AHU proactively.

However, in this case choosing the second recommended policy, should be considered as well. As the opportunistic policy is slightly more expensive due to fact that this replacement is performed at the class survey after 15 years. In both policies the AHU is replaced once over the lifetime of the vessel, only in the opportunistic policy the money is spent five years earlier, making the present value higher. However, there are two big advantages. The first, is the higher level of certainty, replacing the AHU after 15 years, means the replacement is around the MTTF, thus significantly reducing the failure probability. The second, is the elimination of the delivery time, as for this system the delivery time is 4-6 months, it is very likely that a corrective policy leads to an unhappy (freezing of frying, depending on the area of operation) crew for several months. When comparing the recommended policy with the policy currently applied by Anthony Veder, there is no improvement in total cost for the maintenance budget of the AHU, as the recommended policy is the currently applied policy.

6.2.8. Group VIII - Lube Oil Transfer Pump

The eighth system is a lube oil transfer pump. This pump is there to lubricate other systems onboard, this is not a system that is critical for operation and failure of this system does not result in a vetting risk. In table 6.18, the system specific input of a lube oil transfer pump is presented.

Table 6.18: Input Variables - Lube Oil Transfer Pump

Price	€5000,-	**Delivery time**	1 month
Vetting Risk	No	**Repair time**	1 day
Service Engineer	No	**10% Failure**	7417 hours
MTTF	11.569 hours	**90% Failure**	23.750 hours

The data from BASSnet was insufficient to determine the failure probabilities of the lube oil transfer pump. In lack thereof, the average of data from two other sources was used. The explanation of the gathering of this data is in section 6.4. The ranking of the four maintenance policies formed by the MCM, for a lube oil transfer pump is presented in table 6.19.

Table 6.19: Maintenance Policies Ranking - Lube Oil Transfer Pump

Policy	**Cost**	**Replacements**	**Every**	**Failure Probability**
Corrective Maintenance - *o.o.b.d.*	€27.000,-	8	2.7 years	100%
Predictive Maintenance	€30.000,-	9	2.5 years	80%
Opportunistic Maintenance	€31.000,-	9	2.5 year	79%
Corrective Maintenance - *s.1.s.*	€37.000,-	9	2.7 years	100%

Based on the total cost per policy as presented in table 6.19, for the lube oil transfer pump a corrective maintenance policy is recommended. However, all costs are close together and all failure probabilities are high. The recommended corrective policy replaces the pump after 2.7 years, with a high risk of failure before this moment. Due to the low reputation cost, taking this risk is cheaper than replacing the pump proactively. Although the failure probability is high, corrective maintenance, is the most plausible policy. As this system imposes no risk for the operation, storage costs are wasted when storing a spare and use full life is wasted in a proactive policy. Thus, the recommended policy is the corrective -*order on breakdown* policy. When comparing the recommended policy with the policy currently applied by Anthony Veder, there is no improvement in total cost for the maintenance budget of the pump, as the recommended policy, is, the currently applied policy.

6.3. Evaluation of Results MCM

In general it can be concluded from the eight applications that different systems with different conditions generate different outcomes, as illustrated in table 6.20.

Table 6.20: Maintenance Policies Comparison

Group #	**System**	**Recommended Policy**	**Improvement**
Group I	Magnetron X-band	Predictive	1%
Group II	X-band Radar	Proactive	-
Group III	ECDIS	Predictive	3%
Group IV	GPS	Corrective -*o.o.b.d.*	-
Group V	MYCOM Compressor	Corrective -*s.1.s.*	70%
Group VI	CC Room Ventilator	Predictive	49%
Group VII	HVAC Air Handling Unit	Corrective -*o.o.b.d.*	-
Group VIII	Lube Oil Transfer Pump	Corrective -*o.o.b.d.*	-

When evaluating the groups it can be seen that for three of the four groups that influence the operation, either through downtime or via a vetting risk, a proactive maintenance policy is recommended. For three of the four groups where a failure does not influence the operation, a corrective maintenance policy is recommended. Thus, it seems there is a strong correlation between the effect of a system on the operation-ability of a vessel and the proactiveness of the maintenance policy.

Furthermore, in group five, it appears that the relatively high system price in combination with the long delivery time, result in the recommended corrective (store 1 spare) maintenance policy. In chapter 7, an analysis is performed to test these assumptions and identify the decisive parameters of a system for the recommendation of a maintenance policy.

Next to the correlations between certain parameters and the recommended policy it is also interesting to evaluate the improvement percentage. Between the eight groups in four of them the recommended policy leads to an improvement. The average improvement over the 8 groups is, 16% . When only regarding the four groups where the recommended policy is different from the actual applied policy the general improvement is 25%. This is per system or component onboard, so using the MCM to substantiate the maintenance policy for all systems onboard, of all vessels of a fleet, could lead to a substantial financial benefit.

In the case study, eight systems, representing eight groups were evaluated. These systems are not all in agreement with each other. Between these systems there is a large difference in system price, varying from €1500,- to €70.000,-, in MTTF, varying between 0.4 and 15 years, and in delivery time, varying from 1 hour to 9 months. As a result hereof, the effect of these variables has not been properly investigated. Therefor, it is interesting to asses the influence, of the not specifically varied, system price, delivery time and MTTF, on fictitious systems. This influence assessment is performed in chapter 7. But before going to chapter 7, first different failure data calculations are explained and compared.

6.4. Failure Data Comparison

In this research the failure rates are (in general) calculated based on the historic data from BASSnet. However, there are several other methods to obtain failure behaviour to calculate failure rates. Namely;

- OREDA
- Expert Opinion
- Recommendations Manufacturer

As it is valuable to Anthony Veder to know the conservativeness and reliability of each of the different failure data-sets, in this section these four failure rates are compared. First, the three new methods are explained. Thereafter, the comparison is made.

6.4.1. Different Determination Failure Behaviour

In this section the three other, not from historic data from BASSnet, methods of determining failure rate are explained.

OREDA - ”OREDA (Offshore and Onshore Reliability Data Handbook) is a project organisation sponsored by oil & gas companies with world-wide operations” [77]. OREDA has established a databank with reliability and maintenance data of mainly off-shore equipment. Since 1984, six reliability handbooks have been published. In the OREDA handbook the lower & upper bound and mean failure rate of five main system groups are categorised. [77] The five main system groups in OREDA are:

- Machinery
- Electric Equipment
- Mechanical Equipment
- Control and Safety Equipment
- Subsea

Of the eight systems used in this research, two are included in OREDA. This is not a good representation of the use of OREDA, the ratio of systems onboard that are in OREDA is higher than 25%. However, as OREDA does not include any bridge equipment, already 50% of the eight systems is not included in OREDA. The two systems and their MTTF in OREDA are;

Table 6.21: Failure Data - OREDA

System	**OREDA MTTF**
MYCOM Compressor	5.6 years
Lube Oil Transfer Pump	11388 hours

Expert Opinion - Within Anthony Veder there are numerous experts on all the different systems on-board. To gather their knowledge, estimate of the failure behaviour, several expert panel groups where set up. In these groups the experts were interviewed. The work of Kumar [58] is used to get familiar with the research methodology of expert interviewing, which will be used to extract the rationale from experts. The interview technique used for these interviews is a combination of the delphi method [59] and rationale capturing [27].

The delphi method is an interview technique for structuring group communication, allowing a group of individuals to deal with a complex problem [59]. There are various ways to set up a delphi study, however the general concept is always the same. First, a panel of experts is created. Then a question (or questionnaire) is sent to each individual panel member. After this first round, all information is processed and summarised. Then, for the second round the same question (questionnaire) is sent around, asking the same information, however also providing his or her previous answer and a summary of the results from the previous round. In the third round the same information is asked, and again information of the previous round is provided, and so on and so on. Eventually after a few iterations the responses begin to stabilise and approximate. The mean of the panellists' final responses is the expert panel opinion. [30]

Since the failure data alone, does not tell the whole story. An explanation about the rationale of the experts is valuable. Rationale is the reasoning and decision-making process [52]. Knowledge about rationale can be valuable, but is difficult to capture [45]. DeNucci [27] presents a method for capturing configuration rationale in complex ship design. Rationale capturing methods are domain dependent and should be specifically designed to suit the needs of the research [64].

For this research the final iterated group response, failure behaviour, is the main objective. However, the rationale behind the numbers is also considered valuable, therefore it is chosen to include a group discussion in the interview method. Meaning first, the questionnaire concerning failure behaviour of a certain system is distributed and completed by the panel members without interaction. Thereafter, the researcher collects and processes the answers. Following the researcher presents the average answer of the round to the group, therewith initiating a group discussion, about the reasoning of their answers. After the group discussion, the next round starts, again with the panel members filling in the questionnaire concerning failure behaviour individually without interaction. Followed by a group discussion, and so on and so on.

In this approach, two different expert panel groups were set-up, giving their expertise on different systems. In total ten experts were interviewed about eight systems, the same eight systems as used for the first application of the MCM. One expert group concerned the electric systems and the other group the mechanical systems. After a maximum of three, sometimes two, rounds of iteration a consensus answer was found for the failure behaviour. The experts were asked when in their opinion, 10%, 50%, and 90% of a group of 100 identical systems will have failed. This way, after the iterations, being able to determine the MTTF and then compare this MTTF with the other failure data.

The results of the sessions with the two expert panels are presented in table 6.22. The anonymous filled in questionnaires are included in appendix C.

Table 6.22: Failure Data - In-house Experts

System	In-house Experts
Magnetron X-band	0.98 years
X-band Radar	-
ECDIS	5.4 years
GPS	94.960 hours
MYCOM Compressor	5.4 years
CC Room Ventilator	60.000 hours
HVAC Air Handling Unit	15 years
Lube Oil Transfer Pump	11750 hours

Recommendations Manufacturer - Several manufacturers and suppliers, of the eight systems, have been contacted about their recommendations. Some manufacturers were somewhat hesitant to provide information about the lifespan of their system. Not all responded and some responded, recommending a corrective replacement policy, instead of the requested information about the lifetime of the system. The results are presented in table 6.23.

Table 6.23: Failure Data - Manufacturers

System	Recommendation Manufacturer
Magnetron X-band	1 year
X-band Radar	15 years
ECDIS	5 years
GPS	corrective
MYCOM Compressor	-
CC Room Ventilator	43.800 hours
HVAC Air Handling Unit	corrective
Lube Oil Transfer Pump	-

In addition to these it must be said that, no recommendations were made about the MTTF of a system. The recommendations were about when to replace certain systems, no information about the corresponding failure probability was provided.

6.4.2. Comparison Failure Rates

Based on the gathered information, a comparison can be made. An overview of all previously gathered information is presented in table 6.24 and illustrated in figure 6.2.

Table 6.24: Failure Data - MTTF Comparison

System	BASSnet	OREDA	Experts	Manufacturers	
Magnetron X-band	1.1	-	0.98	1	years
X-band Radar	3.2	-		15	years
ECDIS	6.3	-	5.4	5	years
GPS	58.594	-	94.960	corrective	hours
MYCOM Compressor	1	5.6	5.4	-	years
CC Room Ventilator	58.824	-	60.000	43.800	hours
HVAC Air Handling Unit	0.8	-	15	corrective	years
Lube Oil Transfer Pump	-	11388	11750	-	hours

As the failure probabilities of the recommendations of the manufacturers are unknown, caution is required when making a comparison. The the other numbers are all the MTTF. Although the failure probability is unknown it is interesting to observe if the recommendations of the manufacturer are conservative, compared to the MTTF or not. As manufacturers might have a different interest, with regard to the amount of replacements.

Figure 6.2: Comparison of Failure Data

When evaluating the results, no real conclusion can be drawn, due to the small data-set. Except that, preferably no calculations should be made based on one failure information source.

When looking at the information about the X-band Radar, the GPS and the Air Handling Unit, it is observed that the results for all of them are based on two sets of information. And that the numbers are far apart. Based on only two inputs, when they are far apart it is impossible to choose one, since it is not clear which is an outlier.

Three sets of information, is still not enough data to perform a proper statistical analysis. However, it may be possible to identify the outlier. Looking at the CC Room Ventilator it seems the manufacturer is conservative, as the information from BASSnet and the Expert Panel is in agreement. When looking at the MYCOM it seems the information from BASSnet is the outlier, as the information from OREDA and the Expert Panel concedes. Regarding the Magnetron and ECDIS all three sources of information concedes, thus for these two systems there is currently the highest certainty in the failure data.

Looking at the Lube Oil Transfer Pump and the MYCOM, it seems as if the data from OREDA and the Expert Panel concede. More information from different systems is required to substantiate this preliminary result. Based hereupon, when looking for ways to check and validate the failure data obtained from BASSnet, the knowledge from in-house experts as well as the information from OREDA could be valuable.

6.5. Roadmap for Implementation MCM for Anthony Veder

This method for the maintenance cost calculation offers a quick and substantiated total cost per maintenance policy over the lifetime of a vessel. The MCM is generally applicable and proves the concept. For a shipping management company this is important information that ensures improved true operational costs, due to an adapted maintenance approach. The MCM was developed in cooperation with shipping management company, Anthony Veder. To ensure a maximum benefit for Anthony Veder, in this section there is a concrete roadmap for short-, mid- and long-term actions to establish the successful implementation of the MCM:

- Adapt BASSnet to be more suitable for data- collection, analysis and (appropriate) storage for re-use
  - Start at the end with BASSnet: What is the goal of BASSnet?
  - Start logging actual operating hours, for specific systems
  - Import the historic data from Star IPS in BASSnet
  - Reduce the amount of recurring jobs in BASSnet
- Create a broader support for BASSnet amongst the crew
  - Make the crew see the goal and mutual benefits of a correctly implemented BASSnet
  - Train crew in correct (usable) data input in BASSnet
- Develop a live automated data exchange between the (appropriately logged) failure data from BASSnet and MCM
- Appoint a person responsible for implementation and application of MCM (asset manager or maintenance engineer)
  - Researcher explains MCM to asset manager
  - Asset manager uses MCM to determine recommended maintenance policy for every system onboard
  - Asset manager discusses maintenance planning with vessel manager
  - Vessel manager (and asset manager) discuss maintenance planning with vessel operator, to coordinate maintenance and operational planning
  - Asset manager gives Ruud te Selle, the maintenance cost per system for his 5Q budget sheet
  - Asset manager uses MCM for long term budgeting
- Investigate the possibility to be able to log shared spare parts between vessels with the same equipment in BASSnet
- Adapt BASSnet, so that it is possible to change a recurring job (e.g. inspection) to a corrective job, when a failure is detected
- Also consider the 2,5 year compulsory survey as a full opportunity, even consider going to dock and gas freeing, making optimal use of the opportunity.

6.6. Summary

After the development of the MCM, the MCM is applied to calculate the maintenance cost for a group of systems that are onboard the gas tankers of shipping management company, Anthony Veder. In this chapter the findings of this first application of the MCM are presented. Based on this first application of the MCM it is possible to answer the fifth research question:

5. What benefits do an equipment specific change in maintenance policy bring Anthony Veder?

Between the eight tested groups, in four of the groups, the recommended policy leads to cost reduction. The average conservative improvement over the eight groups is, 16% cost reduction. When only regarding the four groups where the recommended policy is different from the actual applied policy the general conservative improvement is 25% cost reduction. Meaning a substantial improvement of the maintenance costs is a direct benefit for Anthony Veder, when applying an equipment specific maintenance policy. To ensure the maximum benefit for Anthony Veder, this chapter was concluded with a roadmap to establish the successful implementation of the MCM.

Reflecting on the case study, the Anthony Veder specific results, eight systems were evaluated which were not all in agreement with each other. Therefore, it is required to asses the influence of the not specifically varied, system price, delivery time and MTTF on fictitious systems. Thus, continuing on the results from the case study, in the next chapter, chapter 7, an analysis is performed. To try and identify the decisive parameters of fictitious systems in the recommendation of a maintenance policy and therewith gain insight in the general maintenance policy decision-making.

7

Maintenance Policy Quantification

In this chapter an analysis is made to test the assumptions resulting from the applications of the maintenance cost model (MCM) and to identify the decisive variables of a system in the recommendation of a maintenance policy. Hopefully while providing novel insights in the general maintenance policy decision-making.

When evaluating the results of the first application of the maintenance cost model (MCM), as presented in chapter 6, there appears to be a correlation between the vessel being operational, despite the failure or repair, and a reactive maintenance policy being recommended. And also the other way around, the vessel no longer being operational, due to the failure or repair, and a proactive maintenance strategy being recommended. To test these assumptions a sensitivity analysis (SA) is performed. The objective of a SA of model output is; “to ascertain how a model depends on its input factors and how uncertainty in the output of a model can be apportioned to different sources of uncertainty in the model input” [69–71].

In this chapter, the dependency of the outcome of the MCM, the cost optimal maintenance policy, on input variables is tested. Since the MCM has 25 variable input factors, it is a thesis research in itself to test the dependency of the outcome, on each of the input variables. Let alone conducting a mixed uncertainty–sensitivity analysis, in which the dependency of and correlation between multiple input factors is investigated simultaneously [70]. Therefore, in this chapter the dependency on the vessel being operational and a corrective policy being optimal, and the vessel not being operational and a proactive policy being optimal is investigated. As this was the most apparent correlation observed after the first application of the MCM. In these two scenarios the dependency of the **system price**, **delivery time** and **MTTF** will be assessed. Based on the not specifically varied system price, delivery time and MTTF, a sensitivity analysis (SA) to asses their influence on the conclusions per group is performed, to ensure the case study conclusions, chapter 6, are valid in general for these groups.

The result of each analysis is displayed in a graph. In which the total cost of the policy is always on the y-axis and the changing variable is on the x-axis. As the cost of the policies on the y-axis are increasing, this means that the optimal policy, lowest total cost,

Figure 7.1: Legend to label Data of Entire Chapter

is the lowest of the four graphs. For clarity throughout the entire chapter, in all graphs, the same colours correspond to the four policies, as can be seen in figure 7.1.

7.1. No Operational Impact Analysis

In this section the scenario where a failure does not impact the operational activity of the vessel is investigated. Meaning that, in the input screen, the three following settings are chosen:

- The vessel is still 100% operational
- Also during repair the vessel is 100% operational
- There is **no** vetting risk induced by the failure

With these three settings, both the off-hire and the reputation costs are zero, for the explanation of this fact you are referred to chapter 4. When the off-hire and the reputation cost are zero, this means that in this analysis the influence of a variable on the replacement cost is tested. First, the influence of the **system price** on the recommended policy is analysed. For this analysis all input variables, except the system price, are kept the same. The results are shown in figure 7.2. As can be seen in the figure, the red graph is always above the other graphs. Thus, the corrective -*store 1 spare* policy (red), is independent of the price never the optimal policy. Based solely on the price variation, it is not possible to draw any conclusion about the other three policies.

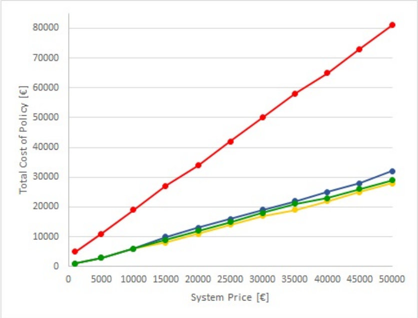


Figure 7.2: Analysis of Fluctuating Price

Following, the influence of the **delivery time** of the system on the recommended policy is analysed. In this analysis all input variables, except the delivery time of the system, are kept the same. The results are shown in figure 7.3. As can be seen in the figure, the red graph is, again in this case, always above the other graphs. Thus, the corrective -*store 1 spare* policy (red), is independent of the delivery time never the optimal policy. It can also be seen, that the yellow, blue and green graphs are all identical. Furthermore it is noticeable, that the delivery time has no impact at all at the height of any of the three policies, indicated by the horizontal graphs. Thus, the delivery time has no impact on the

Figure 7.3: Analysis of Fluctuating Delivery Time

outcome of the model, when the failure has
no operational impact.

Finally, the influence of the **mean-time-to-failure** (MTTF) of the system on the outcome is analysed. In this analysis all input variables, except the MTTF of the system, are kept the same. The results of an increasing MTTF, from one up until ten year(s), are shown in figure 7.4. As can be seen in the figure, the red graph is, again, above the other graphs. Thus, the corrective -*store 1 spare* policy (red), is independent of the MTTF, never the optimal policy. It can also be seen, that the yellow, blue and green graphs are all close together, the difference is negligible, and thus it is not possible to draw any conclusion about the other three policies.

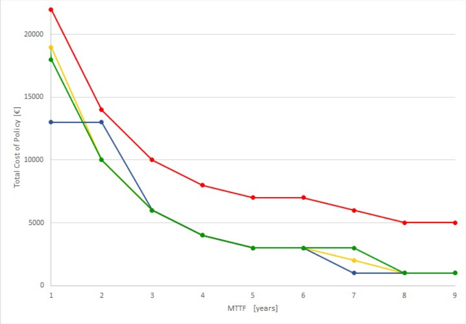


Figure 7.4: Analysis of Fluctuating MTTF (1)

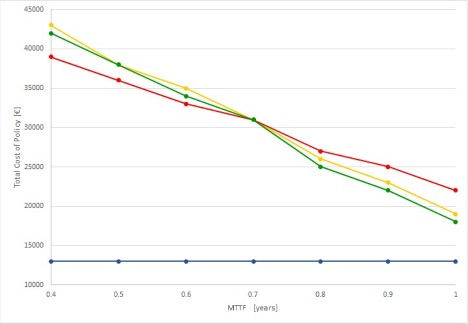


Figure 7.5: Analysis of Fluctuating MTTF (2)

Furthermore, when examining figure 7.5, a varying MTTF of 0,4 up until 1 year, it is obvious that the opportunistic maintenance policy (blue) is the optimal. This is due to fact that the first opportunity in an opportunistic policy arises after 2.5 years. Therewith, the total amount of replacements is in an opportunistic maintenance policy limited to a maximum of nine over the lifetime of the vessel. Thus, a MTTF below a year has no influence on the cost of an opportunistic maintenance policy. However, when applying an opportunistic policy in this way, it is almost as applying a corrective policy as the probability of a failure appearing before the opportunity is significant. Furthermore, a MTTF below one year raises other questions, such as is this the right system for the job, is a warranty claim with the manufacturer an option, is there human error involved? However, as these topics are outside the scope of this research, the MTTF below one year will not be further discussed.

Concluding, when evaluating the price, delivery time and MTTF in a scenario where the failure or repair has no operational impact, it can be concluded that:

- Independent of the price, delivery time or MTTF the maintenance policy, corrective -*store 1 spare*, is not the optimal choice.
- The delivery time of the system has no influence on the cost of the policy.
- 75% of the tested systems without operational impact, in the first application of the MCM, chapter 7, resulted in a reactive (corrective -*order on breakdown* policy, but from the analysis performed here this conclusion can not (yet) be drawn or refuted.
- To further determine the effect of the system price and the MTTF on the

maintenance policies. A mixed uncertainty–sensitivity analysis of these two variables is required.

7.2. Operational Impact Analysis

In this section the scenario where a failure does affect the operational activity of the vessel is investigated. Meaning that, in the input screen, the three following settings are chosen:

- The vessel is **not** operational
- Also during repair the vessel is **not** operational
- There **is** a vetting risk induced by the failure

With these three settings, the off-hire and the reputation costs are no longer zero, for the explanation hereof you are referred to chapter 4. When the operational activity of the vessel in impacted, the off-hire and the reputation cost are part of the total cost per policy.

First, the influence of the **system price** on the recommended policy is analysed. For this analysis all input variables, except the system price, are kept the same. The results are shown in figures 7.6 and 7.7. In figure 7.6, a price increase from €0 to €100.000,- is shown. In this chart it can be seen that from €0 until around €65.000,- a corrective -*store 1 spare* policy (red) is optimal. Thereafter, from €65.000,- until €100.000,- a predictive maintenance policy (green) is recommended. The similarity between these two policies is that both do not have delivery time (incorporated in the downtime), for explanation hereof see chapter 4. As in the previous section, section 7.1, it was established that a mixed uncertainty–sensitivity analysis between price and MTTF is desirable. It is decided to perform the same price influence analysis, only with a different MTTF. The results hereof are shown in figure 7.7, all other settings are kept identical. Also, the price variation is again between €0 and €100.000,-.

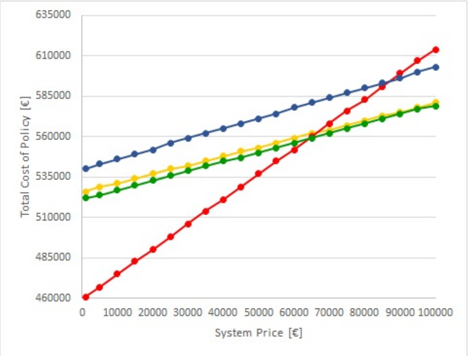


Figure 7.6: Analysis of Fluctuating Price (1)

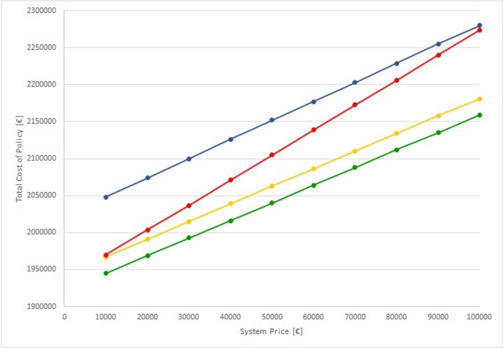


Figure 7.7: Analysis of Fluctuating Price (2)

As can be seen in figure 7.7, the optimal policy independent of a fluctuating price is in this case a predictive one (green). Based on these two graphs it is too soon to conclude that it will always be corrective -*store 1 spare* or predictive. What can be said though is that the gradient of the graphs does not change. Showing the same gradient and distance between the green, yellow and blue graph in figures 7.6 and 7.7, and the same gradient of the red graph in both figures as well. Only the point of intersection between the two graph differs, resulting in a critical difference in outcome.

Furthermore, when comparing figure 7.2 with figure 7.6, a clear influence of the operational impact can be seen. The green, predictive, and red, corrective -*store 1 spare*, graphs have moved below the yellow graph of the corrective -*order on breakdown* policy. A shift from a reactive to a proactive policy, as was also ascertained after the first application of the MCM, in chapter 7.

Second, the influence of the **delivery time** of the system on the recommended policy is analysed. In this analysis all input variables, except the delivery time of the system, are kept the same. The results are shown in figures 7.8 and 7.9. In figure 7.8, an increase in delivery time from 0 to 48 hours is shown. In this figure first a predictive policy (green) is recommended, after approximately 11 hours a corrective -*store 1 spare* policy (red) is recommended. As the dual comparison, performed above in the price analysis was deemed interesting, also here a second analysis of fluctuating delivery times with a different MTTF is performed. The results hereof are shown in figure 7.9, all other settings are kept identical. Also, the delivery times are again increased from 0 to 48 hours.

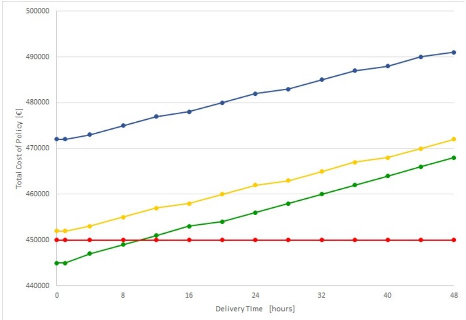


Figure 7.8: Analysis of Fluctuating Delivery Time (1)

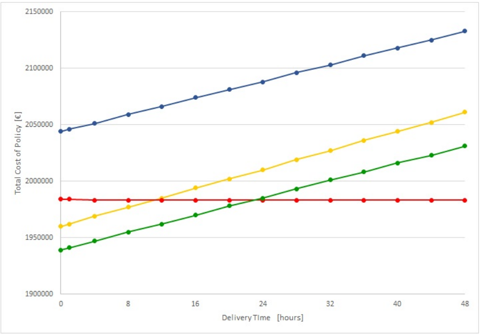


Figure 7.9: Analysis of Fluctuating Delivery Time (2)

As can be seen in figure 7.9, the course of the graph is the same as in figure 7.8. First, a predictive policy (green) and then the corrective -*store 1 spare* policy (red) is optimal. However the intersection, where the policy switch occurs, is different. First, this was at 11 hours, now this is at 24 hours. Meaning that changing the MTTF changes the moment of the tipping point between the two policies. Furthermore it is obvious, that increasing the delivery time has no impact at all at the height of the corrective -*store 1 spare*, indicated by the horizontal red graphs.

Finally, when comparing figure 7.8 with figure 7.3, a clear influence of the operational impact can be seen. The green, predictive, and red, corrective -*store 1 spare*, graph are now both below the yellow graph of the corrective -*order on breakdown* policy. Where in figure 7.3 there green and yellow were equal and the red was far above both. Now a shift to a proactive policy is visible, as was also noted after the first application of the MCM, in chapter 7 and in the price SA.

Now, the influence of the **mean-time-to-failure** (MTTF) of the system on the outcome is analysed. In this analysis all input variables, except the MTTF of the system, are kept the same. The results of an increasing MTTF, from one up until ten year(s), are shown in figure 7.10. As can be seen in the figure, all graphs are close together and the optimal policy is volatile, thus based solely on the MTTF variation, it is not possible to draw any conclusions. When examining figure 7.11, a varying MTTF of 0,1 up until 2 year(s), it is obvious that again in the beginning the opportunistic maintenance policy (blue) is the optimal. This is for the same reason as explained before, the first opportunity in an opportunistic policy arises after 2.5 years.

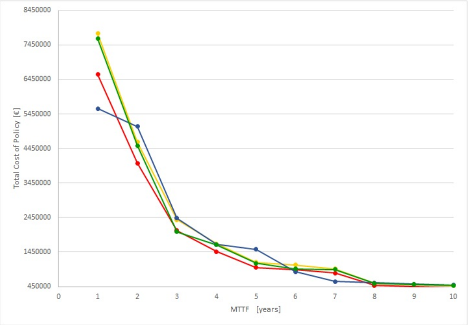


Figure 7.10: Analysis of Fluctuating MTTF (1)

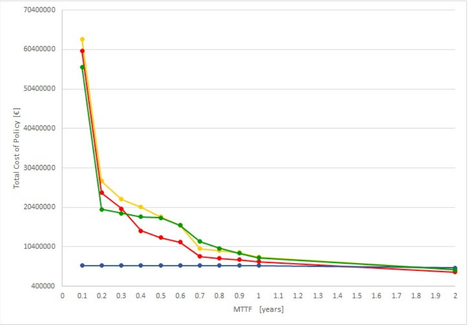


Figure 7.11: Analysis of Fluctuating MTTF (2)

Based on the MTTF analysis no conclusions can be drawn. Also comparing figures 7.4 and 7.5 with figures 7.10 and 7.11 does not lead to any valuable insights. However, the difference between the system price and delivery time graphs with a different MTTF show us, that MTTF has an influence and further research is required.

Concluding, when evaluating the influence of price, delivery time and MTTF in a scenario where the failure or repair has an operational impact, it can be concluded that:

- Fluctuations in system price, delivery time and/or MTTF influence which policy is optimal.
- A modest shift from a corrective -*order on breakdown* to a more proactive policy was ascertained between the scenario without operational impact, to the scenario with operational impact.
- 75% of the tested systems with operational impact, in the first application of the MCM, chapter 7, resulted in a proactive (predictive or opportunistic) policy. The remaining 25% in the corrective -*store one spare* policy, thus 0% of the time corrective -*order on breakdown* was recommended, however from the analysis performed here this conclusion can not (yet) be drawn or refuted.
- To further determine the effect of the MTTF on maintenance policies. A mixed uncertainty–sensitivity analysis of MTTF and other input variables is required.

7.3. Summary

In this chapter different uncertainties of the input of the MCM were analysed, focusing on the operational impact, system price, delivery time and MTTF. In the analysis of the optimal maintenance policy recommended by the MCM, the sensitivity analysis results can be summarised as follows:

- When a failure of a system has no operational impact, independent of the price, delivery time, or MTTF the maintenance policy, corrective -*store 1 spare*, is not the optimal choice.
- When a failure of a system has no operational impact, the delivery time of the system has no influence on the cost of the policy.
- A modest shift from a corrective -*order on breakdown* to a more proactive policy was ascertained between the scenario without operational impact, to the scenario with operational impact.
- 75% of the tested systems without operational impact, in the first application of the MCM, resulted in a reactive (corrective -*order on breakdown* policy, but from this SA this conclusion can not (yet) be drawn or refuted.
- 75% of the tested systems with operational impact, in the first application of the MCM, resulted in a proactive (predictive or opportunistic) policy. The remaining 25% in the corrective -*store one spare* policy, thus 0% of the time corrective -*order on breakdown* was recommended, however from the analysis performed here this conclusion can not (yet) be drawn or refuted.
- To further determine the effect of the MTTF on maintenance policies. A mixed uncertainty–sensitivity analysis of MTTF and other input variables is required.
- Also, to establish more insight in how the uncertainties of the input of the MCM contribute to the overall uncertainty, further (mixed uncertainty–) sensitivity analyses are required.

All separate conclusions as summarised above, can be considered novel insights in the general maintenance policy decision-making. Thus, together improving the general maintenance decision-making and therewith providing an answer to the final and sixth research question:

> 6. *How does the developed method help improve the general maintenance policy decision-making, and what insights can be gained from this?*

With answering the last supporting research question, it is now possible the answer the main research question. This, and other general conclusions based on the performed study, are presented in the next chapter, chapter 8.

8

Conclusions

In this thesis, a model for maintenance cost of vessels was presented. The main question that is answered in this thesis is:

> *"To what extend are the true operational costs of a vessel improved by applying an adapted maintenance approach?"*

To answer this question, six supporting questions have been answered. Through answering these questions the researcher was able to understand the context of the problem and work towards an answer to the main research question. The supporting questions are:

1. What are suitable methods to calculate the total cost over the lifetime of a vessel?
2. What are the indirect costs of vessel operation, and how can these costs be quantified?
3. What are the maintenance policies currently applied in shipping, and which of these policies are suitable and relevant to include in this research?
4. What could be a method to be able to calculate and compare the total cost per maintenance policy?
5. What benefits do an equipment specific change in maintenance policy bring Anthony Veder?
6. How does the developed method help improve the general maintenance policy decision-making, and what insights can be gained from this?

The answers to these questions are found in consecutive order in this thesis, of which a summary is presented here.

What are suitable methods to calculate the total cost over the lifetime of a vessel?
For the development of a cost model for vessels the primary interest is in total cost of ownership (TCO). Where needed aspects from life cycle cost (LCC), like including failure behaviour in cost calculations are integrated in the TCO method. Focusing primarily on TCO is the best approach for an unique maintenance cost model for vessels, as explained in chapter 2.

What are the indirect costs of vessel operation, and how can these costs be quantified?
As explained in chapter 2, loss of reputation, loss of hire, loss of a long-term time-charter and rejection by client, are risks of unforeseen maintenance. The indirect

costs resulting from a ban of the vessel need to be included in the cost model. The requirement of a ”Condition of Class” (CoC) is the most obvious way to quantify these indirect costs of vessel operation.

What are the maintenance policies currently applied in shipping, and which of these policies are suitable and relevant to include in this research?
Based on the analysis performed in chapter 3, corrective, opportunistic and usage-based predictive maintenance are deemed the most suitable and relevant maintenance policies for this research, therefore these three policies are included in the development of the method.

What could be a method to be able to calculate and compare the total cost per maintenance policy?
In chapter 4 a model, the Maintenance Cost Model (MCM) is presented. The MCM integrates actual behaviour data from a vessel in the maintenance cost estimation. The actual data from the vessels is used to determine the failure behaviour of the systems onboard. This failure behaviour is used to calculate the actual failure rate and mean-time-to-failure. Based on this actual data, the replacement-, off-hire, and reputation cost are calculated. Combined resulting in different total cost per maintenance policy per system. The Maintenance Cost Model generates a ranking of the maintenance policies, based on lowest cost. The outcome of the MCM, a policy ranking, can be used by shipping management companies, to obtain a better substantiated system specific maintenance policy.

What benefits do an equipment specific change in maintenance policy bring Anthony Veder?
In the case study, as presented in chapter 6, in 50% of the evaluated groups the equipment specific recommended policy leads to an improvement, cost reduction. The average improvement over the eight groups is, 18%. When only regarding the four groups where the recommended policy is different from the actual applied policy, the general improvement is 29%. Meaning a substantial improvement of the maintenance costs is a direct benefit for Anthony Veder.

How does the developed method help improve the general maintenance policy decision-making, and what insights can be gained from this?
In chapter 7, the influence of the, in the case study not specifically varied system price, delivery time and MTTF is assessed. This sensitivity analysis provided the following novel insights in the general maintenance policy decision-making:

- When a failure of a system has no operational impact, independent of the price, delivery time, or MTTF the maintenance policy, corrective -*store 1 spare*, is not the optimal choice.
- When a failure of a system has no operational impact, the delivery time of the system has no influence on the cost of the policy.
- A modest shift from a corrective -*order on breakdown* to a more proactive policy is ascertained between the scenario without operational impact, to the scenario with operational impact.
- To further determine the effect of the MTTF on maintenance policies. A

mixed uncertainty–sensitivity analysis of MTTF and other input variables is required.

- Also, to establish more insight in how the uncertainties of the input of the MCM contribute to the overall uncertainty, further (mixed uncertainty–) sensitivity analyses are required.

The goal of this research is to present a way to improve the maintenance cost calculation of shipping management companies, especially for those with a profit objective. This research presents a model, the Maintenance Cost Model (MCM). This novel approach for the maintenance cost calculation, offers a quick and substantiated total cost per maintenance policy over the lifetime of a vessel. For a shipping management company this is important information, that ensures improved true operational costs due to an adapted maintenance approach. The developed model in this research is generally applicable and proves the concept.

To answer the research question, the achieved cost reductions varied from 0% to 70%, with a conservative average of 16%. As this is a cost reduction per system onboard, using the MCM to substantiate the maintenance policy for all systems onboard, of all vessels in a entire fleet, could lead to a substantial improvement of the true operational costs for any shipping management company.

Next to these improved operational costs, the successful implementation and application of the MCM also provided valuable novel insights in the general maintenance policy decision-making. Therewith, contributing to the body of knowledge of maintenance decision-making in general.

9

Future Research

In this chapter, suggestions for further research are presented, based on the findings of this research and the findings of the literature review. The suggestions for further research are two fold, expanding the Maintenance Cost Model (MCM) and further research into maintenance in shipping in general.

Starting with the first, recommendations for the expansion of the MCM by means of including:

- Increase likelihood of replacements - To approach a more realistic likelihood of replacements for all four policies, an option could be to simulate (e.g. Monte Carlo Simulation) for a certain time-period the values, based upon the reciprocal distribution that has been estimated. When simulating, the observed variation can be better quantified and several scenarios can be tested, and labelled as optimistic and pessimistic. When the simulation is run often enough for several different cases, (i.e. Monte Carlo), the boundaries of the different cases can be established.
- Business cycle predictions in the opportunistic calculations - Currently, the only opportunities in the opportunistic policy are the compulsory class surveys, however obviously there are more opportunities during the operational life of a vessel, due to market conditions. Including these opportunities could make the opportunistic policy generally more realistic and cost effective.
- Ageing systems not suitable for storage - Some systems (e.g. gps, gas measurement cells) are not suitable to be stored, as these degrade on the shelf. When this is the case, the corrective - *store 1 spare* policy should not be recommended.
- Expand the MCM from one vessel to a fleet - Expanding the MCM and incorporating inter-dependencies between vessel of a fleet, allowing the possibility to share 1 spare (per operational area/continent?) for vessels with the same systems (e.g. mycom). Also allowing the possibility to shift cargo when a certain vessel in not operational or rejected by the client. In both situations the economic consequences of a failure decrease. Furthermore, when regarding a entire fleet, it becomes possible to include the

long term reputation damage on the basis of the figures from a company specific risk matrix.

- Develop a live automated data exchange between the (appropriately logged) failure data from PMS and MCM - With automated failure date from a PMS appropriately stored for re-use, the calculations of the MCM are always up-to-date and even more accurate.
- Crew welfare cost - Include cost for crew welfare, as with the air condition system an unhappy crew for six 6 months is maybe not the optimal situation.
- Operating hours - Make distinction between systems where operating hours are being logged, allowing for a more accurate prediction of the MTTF.
- Condition-based maintenance - Include the option to recommend a system specific condition-based maintenance policy, if for instance the failure data is too far apart. Further research in condition-based maintenance in shipping is here-fore required.
- Further develop MCM to be able to also substantiate design decisions

Additionally, a few recommendations for wider research into maintenance in shipping, follow from findings in the literature review and analysis of the model outcome.

- First, to further determine the effect of the MTTF on maintenance policies. A mixed uncertainty–sensitivity analysis of MTTF and other input variables of the MCM is required.
- Second, to establish more insight in how the uncertainties of the input of the MCM contribute to the overall uncertainty, further (mixed uncertainty–) sensitivity analyses are required.
- Also, research into the potential of condition-based maintenance in shipping is required. Investigate when it is beneficial to recommend a system specific condition-based maintenance policy, thus research into implementation costs of condition-based maintenance and the success-rate is recommended.
- Finally, more research is required towards more efficient maintenance policies in shipping as a whole. The shipping industry can learn from other industries, as other industries might be more inclined or forced to innovate.

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