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Modelling Maintenance – Cost Optimised Maintenance in Shipping

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Abstract

Most ship management companies base the operational cost calculation on scheduled maintenance jobs. Scheduled maintenance jobs do not take unforeseen maintenance into account. This underestimates the operational budget. The estimation of the operational costs can be improved by including the unforeseen maintenance costs. The amount of unforeseen maintenance costs depends on the implemented maintenance policy, as well as the failure and maintenance intervals. To study this interaction a model is required. A Maintenance Cost Model (MCM) is developed and validated to demonstrate the impact of maintenance policies at Anthony Veder. This model focuses on maintenance cost calculations for different maintenance policies, based on failure behaviour. Anthony Veder will be able to save 60% on average on maintenance costs of mechanical equipment by optimising their maintenance policies. Although applied to Anthony Veder the developed model is generally applicable offering ship management companies' insight in suitable maintenance options.

1. Introduction

Currently, the operational costs of a vessel are estimated in the investment decision-making process, based upon experience and market-information, *van IJserloo (2020)*. A more detailed estimate of the operational costs is made for a short-term period. This estimate is also based on the maintenance jobs scheduled for that short-term time-period. Thus, unscheduled repairs are not taken into account in either of the operational cost estimations. In general, maintenance costs are approximately 40% of the total operational cost of a vessel. Of these maintenance costs, 20% are unscheduled repairs, *van IJserloo (2020)*. Thus, not taking into account the unscheduled repairs when estimating the operational costs, means approximately 8% of the total operational costs are missing.

Especially in the Oil and Gas industry, there is a strong focus on a safe reputation, unforeseen maintenance is therefore not only a cost element, but also impact the reputation of the entire company, far beyond the single vessel. 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, which examines the whole management of fleet and office, *Bijwaard and Knapp (2009), Hull (2007).* Loss of hire, or even loss of a long-term time-charter can follow an incident. Since TMSA audits examine the whole fleet, this means a defect on a vessel not utilised by the concerning oil major can affect the outcome of an audit by this oil major. Therefor vetting inspections create a strong commercial incentive for ship owners and/or management companies, *Knapp and Franses (2006), Mathur (2018), Cefic (2011).*

This resulting long-term reputation damage, exists more on fleet and company level, as certain clients evaluate the whole fleet and evaluate the management-system and can far exceed the vessel value, *Heijboer (2019), Bijwaard and Knapp (2009), Hull (2007), Knapp and Franses (2006).* Next to the long-term reputation damage, there are also short-term reputation costs. Short-term reputation costs are the reputation costs directly induced by a failure on a particular vessel. This can be loss of hire or also being less flexible at the spot-market as it is not possible to transport all cargo of all clients.

In order to keep costs predictable and thus enhance the competitive advantage, every (ship management) company, with a profit objective, needs to be in complete control of all assets, *Ellram and Siferd (1998), Su et al. (2015), Mathur (2018)*. Therefore, every ship management company needs a valid and accurate estimate of the total operational cost of a vessel. Besides total cost calculations, the trade-off between repair and replacement is crucial for a proactive management strategy, *Handlarski (1980)*. For which it is essential to be able to accurately predict the cost associated with unscheduled repair and/or replacement of systems on board a vessel. To be able to make a better substantiated trade-off, information about failure behaviour and the mean-time-to-failure (MTTF) are key. In order to calculate the operational costs, this paper presents an improved cost estimation, based on equipment-specific maintenance costs. Such a method should be able to:

- calculate and compare the maintenance share of the total operational cost;
- consider the lifetime of a vessel;
- looking from an owners' perspective;
- include direct and indirect cost of vessel operation;
- compare different maintenance policies.

1.1. Literature Review

Based on the requirements, 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, a literature review is presented about, maintenance policies and cost estimation methods.

1.1.1. Maintenance Policies

In recent years different maintenance techniques, have been researched, compared and documented, *Ahmad and Kamaruddin (2012)*. There is an extensive amount of research concerning maintenance policies in capital intensive industries, *Tinga (2013)*. Such as the process industry, energy generation industry, manufacturing industry and air, rail, and road transport industry, *Hassanain et al. (2003), Chang and Ni (2007), Cooper and Haltiwanger (1993), Wang (2000), Dekker and Scarf (1998), Callewaert et al. (2018), Chen et al.(2012), Koornneef et al. (2017), Verhagen and Curran (2013), Zorgdrager et al. (2013), Nunez et al. (2014)*. Fig.1 shows a subdivision between the different policies is illustrated, *Tinga (2013)*. As shown in the overview, maintenance is divided in three main branches, namely reactive, proactive and aggressive. In the following sections these maintenance policies are evaluated per branch.

<u>Aggressive maintenance</u> involves adapting the equipment, by redesign or modification, to decrease the amount of failures. An improved system often requires less maintenance, *Tinga (2013)*. Aggressive maintenance can be beneficial in multi-component systems, it is applied in railway, aerospace and shipping amongst others, *Su et al. (2015), Vu et al. (2014), Nicolai and Dekker (2008)*. 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.

<u>Reactive maintenance</u> is performed <u>after</u> 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. Reactive maintenance is divided in *corrective* and *detective* maintenance *de Jonge et al. (2017), Tinga (2013).*

<u>Corrective</u> maintenance can be more expensive than proactive 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 *de Jonge et al. (2017)*. However, when a 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.

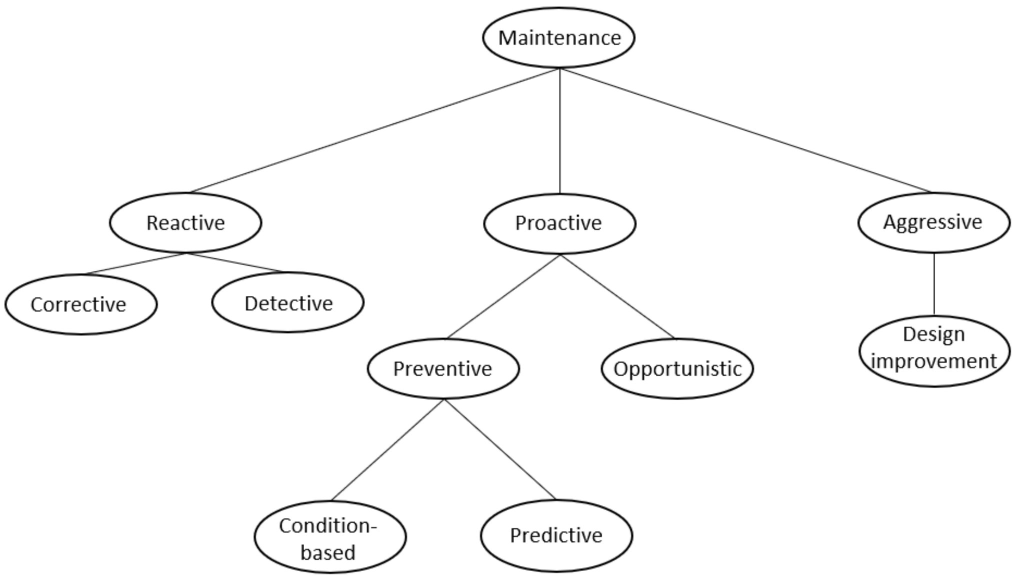

Fig.1: Classification of Maintenance Policies

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, *Tinga (2013)*. Thus, this policy is very limited in the choice of systems. Therefore, detective maintenance is not included in this research. Both corrective and detective maintenance are costless policies, since no data needs to be collected, stored and/or monitored. Furthermore, no remaining useful life of the system is wasted.

Proactive maintenance is performed before a system fails. The proactive maintenance policies are divided into preventive and opportunistic.

Opportunistic maintenance is about clustering maintenance tasks to obtain time and/or cost benefits. An opportunity is any moment in time at which a system can be maintained preventively without obtaining extra cost for the downtime of the system, *Dekker and Dijkstra (1992), Dekker and Smeitink (1991), Zhang and Zeng (2015).*

Preventive maintenance can be condition-based or predictive, *Budai et al. (2006), Barlow and Hunter (1960)*.

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 performed when it is necessary.

In predictive maintenance, other methods (e.g. operating hours or loads) are used to determine the optimal interval for maintenance, *Tinga (2010)*.

Condition-based maintenance requires several years of data, *Veldman et al. (2011), Verhagen et al. (2017), Tinga (2013)*. Furthermore, condition-based maintenance is a more expensive policy, of which the relative benefit decreases when the uncertainty of the failure threshold increases, *de Jonge et al. (2017)*. Therefore, it is logical to first, determine with a cheaper preventive method, for which system condition monitoring could be beneficial. This becomes clearer when examining Fig.2. If a predictive policy results in a failure prediction with a low standard deviation ($\sigma = 0.5$), it is superfluous to apply the more expensive condition-monitoring. A failure prediction resulting in a high standard deviation ($\sigma = 3$), condition-monitoring of this (sub)system could result in a more accurate prediction and then be a worthwhile investment.

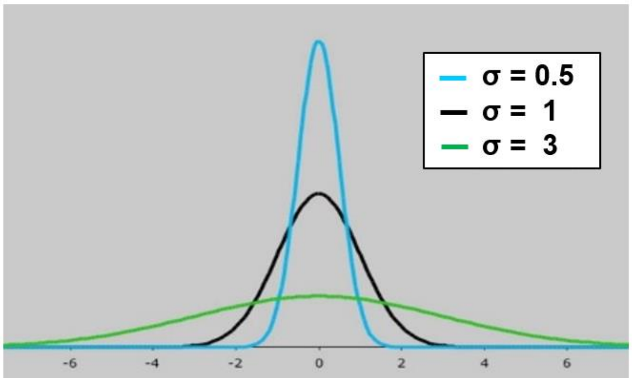

Fig.2: Normal Distribution with Same Mean and Different Standard Deviation

Much research has gone into comparing maintenance policies in clearly defined situations. To do this a cost model is required, however none have focused on shipping, so a suitable cost model needs to be identified as well.

1.1.2. Cost Estimation Methods

Both total costs of ownership (TCO) and Life Cycle Costing (LCC) are extensively used in literature. However no consistent difference can be deduced from literature and in this area the terms seem to be interchangeable as far as the literature goes, *Ellram (1993, 1994, 1995, 1996, 1999), Ellram and Siferd (1993, 1998), Jackson and Ostrom (1980), Fabrycky (1987), Fabrycky and Blanchard (1991), Ferrin and Plank (2002), Hanson (2011), Silva and Fernandes (2006), Barringer and Weber (1996), Wolters (2015)*. The following elements are found to be important for the considered cost model: Direct costs, indirect costs, split into capital costs and operational costs, *Chiadamrong (2003), Parra and Crespo (2012), Roda and Garetti (2015), Shields and Young (1991)*. Finally, a time value of money is to be considered, often the Weighted Average Costs of Capital (WACC) is used for this, though other measures exist, *Barreneche et al. (2015), Fernandez (2010)*. In this paper WACC will be used as it includes the time aspect and can be directly related to the company under investigation.

1.2. Problem Definition

The estimation of the maintenance costs can be improved by including the unforeseen/unscheduled maintenance in this calculation. Determining the optimal maintenance policy is required for the calculation of the corresponding costs. Calculating the cost of a maintenance policy requires the prediction of failure behaviour of a system, *Tinga (2013), Duffuaa and Raouf (1999), Dhillon (2002), Zaal (2011), OREDA (2015)*. To predict or estimate failure behaviour of a system, performance data from the planned maintenance system (PMS), utilised by ship management companies, is required. The previous section illustrated that current approaches to determine total cost of an asset are diverse. No domain-specific TCO or LCC model was found in literature. Furthermore, section 1.1.1 illustrated that the amount of maintenance policies available is incredibly diverse.

Concluding, optimal maintenance is equipment specific and depends on a number of factors. To correctly assess the benefits of changing a maintenance regime a Total Cost Model is required. No such model is available tailored to shipping. For a ship management company maintenance cost estimates can be vital information, that enable a better substantiated total operational cost calculation. Herewith reducing financial risk and therefore contributing to a future proof and healthy company.

2. Method

Different maintenance policies are the basis of the Maintenance Cost Model (MCM) to allow a substantiated maintenance cost calculation.

2.1. Scope

This research covers the unforeseen maintenance cost of the operational cost. It only addresses maintenance-related cost, induced by unforeseen maintenance and does not include routine maintenance jobs, such as greasing, lubrication, painting, etc. The method is developed to make a better-informed maintenance policy decision and not to substantiate design decisions. The model calculates the maintenance cost, with the focus on the systems and engines. Over the entire lifetime 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 considered a failure, *OREDA (2015)*. This means that when a component of a system has failed, this does not necessarily mean the whole system has failed. As discussed in the literature part, the following maintenance policies are considered relevant, corrective, opportunistic and predictive, this is further elaborated upon below. Furthermore, the scope of the indirect costs as described in the introduction will be limited to the short term, vessel related costs. The measurable effect of the vetting risk is the requirement of a "Condition of Class" (CoC). When a CoC is the result of a failure, the vessel is allowed to sail according to class. There are, however, clients that do impose consequences. It is obvious that no sailing, in whichever form, has a direct negative impact on possibility to generate income for a vessel.

2.2. Maintenance Policies

The literature review describes the general maintenance techniques and policies as described in academic literature. This paragraph analyses the suitability of the different polices to the defined problem.

Different maintenance policies require different data as input, dependent on, for example the level of monitoring. In Table I the different policies are ranked based upon the required input data per policy, as explained in the previous section. Starting with the policy that requires the least data. In the second column of Table I, the cost, represent the (implementation) cost of the policies. This is not the cost of the maintenance itself. In the third 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. Finally, in the last column the source of this information is presented.

Table I: Maintenance Policies Categorised

Maintenance Policy	Required Data	Cost	Useful Life	Based Upon Research
Corrective	none	zero	no	*Tinga (2013, 2010), de Jonge et al. (2017)*
Opportunistic	none	zero	yes	*Budai et al. (2006), Barlow and Hunter (1960), Dekker and Dijkstra (1992), Dekker and Smeitink (1991)*
Predictive	recommendations from manufacturer	low/ medium	yes	*Zaal (2011), Verhagen and de Boer (2018), Handlarski (1980)*

All maintenance discussed approaches are relevant for this research with the exception of aggressive maintenance, as explained. Detective maintenance is limited in the choice of systems. Therefore, detective maintenance is not included in the model. Condition-based maintenance is more expensive than predictive maintenance and at the moment of this research there is not several years of data available, therefore condition-based maintenance policies are not included in the method. Based on the performed analysis, corrective, opportunistic and predictive maintenance are deemed the most suitable and relevant maintenance policies for this research, these three policies are included in the method.

2.3. Maintenance Cost Model

Calculating the cost of a maintenance policy requires the prediction of failure behaviour of a system *Tinga (2013), Duffuaa and Raouf (1999), Dhillon (2002), Zaal (2011), OREDA (2015).* To predict or estimate failure behaviour of a system, performance data from the planned maintenance system (PMS), utilised by ship management companies, is required. Making calculations based on practical data, with a range of parameters over a vast range of possible scenarios, involves solving several equations and considering interactions between the different systems. A mathematical model calculating the maintenance cost of a system, for different scenario's and incorporation uncertainties is developed. The gap in the existing knowledge is, an accurate maintenance cost model for vessels, based upon/comparing several maintenance policies.

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 Fig.3. Based on operational input data, the mean-time-to-failure (MTTF) of a system is calculated. Where after, for each maintenance policy, the total costs are calculated. Finally, the calculated total costs per policy are compared. A ranking of maintenance policies is outcome of the model.

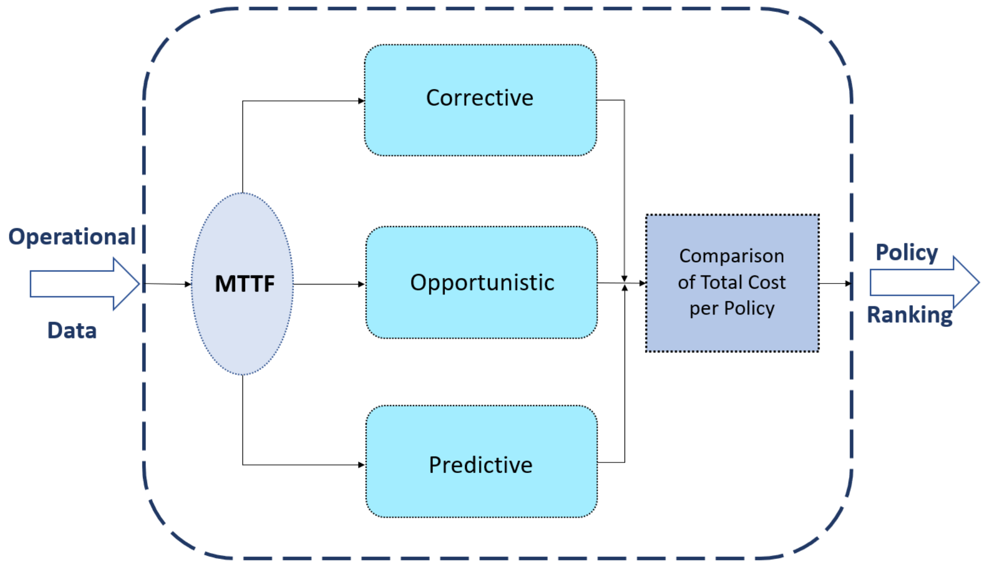

Fig.3: Abstract Representation of Maintenance Cost Model

As illustrated in Fig.3 the cost calculations are performed separately for each maintenance policy. The same three main costs items are calculated for every policy, which together form the total cost per 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/component, per failure. To avoid repetition the explanation of the model is given per main cost item. First explaining the general cost calculation, then highlighting the (potential) differences between the policies.

The delivery time of systems can be substantial, *Zaal (2011), Tinga (2013)*. When ordered at the moment of breakdown, this can result in long off-hire time. This often directly results in a proactive policy being optimal. Therefore, two separate tracks within the corrective maintenance policy are investigated. Namely, a corrective policy where the system or component is ordered after breakdown and a corrective policy with one spare system or component stored, and thus directly available. The MCM effectively compares four different policies:

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

In this research, for both opportunistic and predictive maintenance, an optimisation is performed to find the optimal moment to perform maintenance before failure, based on failure probability from 10% to 90%, with 10% increments. Based on, *Chang and Ni (2007), Dekker (1995), Dekker and Dijkstra (1992), Dhanisetty et al.(2015), Handlarski (1980), OREDA (2015), Zaal (2011)*, a 90% failure probability is utilised to determine the time-to-failure, for the two corrective maintenance policy calculations.

2.3.1. Mean-Time-To-Failure Calculation

As seen in Fig.3 the mean-time-to-failure calculation is the first step in the model. Based upon historic performance data from the PMS, the MCM calculates the MTTF of every system. The two-parameter Weibull distribution is a failure rate description commonly used in reliability engineering, *Khatab et al. (2012), Wang (2000), Dekker and Dijkstra (1992), Dekker and Smeitink (1991), Dekker and van Rijn (1996), Tinga (2013), Grall et al. (2002), Zaal (2011).* This distribution is often used, because it has a correlation between the failure rate and time, and it allows a varying shape parameter. This varying shape parameter means that it is possible to describe both a decreasing, constant and increasing failure rate, *Tinga (2013), Dekker and van Rijn (1996)*.

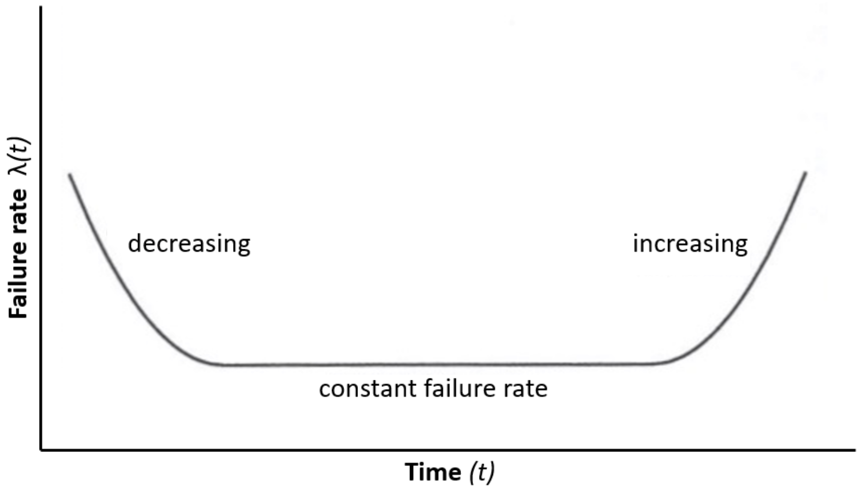

Fig.4: Bathtub Curve

Illustrated in Fig.4 is the bathtub curve, the combination (superposition) of a decreasing, constant and increasing failure rate. Since systems on board a vessel are numerous and diverse, it best suits this research to work with a theory that supports all three failure rates. The Weibull distribution, as presented in Eq.(1), is applied in the model.

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

In the probability density function of the Weibull distribution, η is the scale parameter, which represents the characteristic life of the system or component. β is the shape parameter, which indicates the failure behaviour. The value of β indicates in which phase of its operational life a system or component is, see also Fig.4 for further clarification.

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

From the Weibull distribution, the equation for the MTTF is derived, *Tinga (2013), OREDA (2015), Zaal (2011)*. Equation 2 presents the MTTF equation.

$$MTTF = \eta * \Gamma\left(1 + \frac{1}{\beta}\right) \qquad (2)$$

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

2.3.2. Replacement Cost Calculation

The replacement costs are the direct costs induced by maintenance. Replacement cost in this research refer to direct costs belonging to the replacement of a system or component. These costs consist of the six elements as presented in Fig.5.

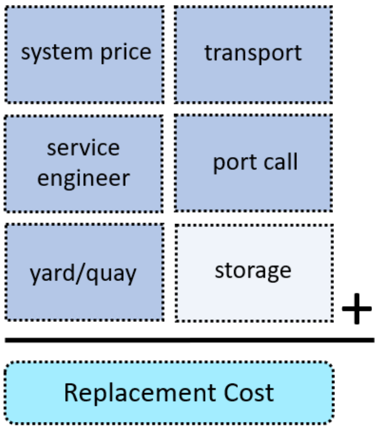

Fig.5: Abstract Representation Replacement Cost Calculation

There is a difference in the replacement cost calculation between the policies. E.g., when applying the corrective maintenance - order on breakdown, there are no spares stored, thus no storage cost.

Opportunistic maintenance is a proactive maintenance policy. Meaning that action is taken before a failure occurs. In the shipping industry a very apparent opportunity presents itself with the compulsory 2.5-year class survey. In this maintenance policy calculation, 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.

Predictive maintenance is also a proactive maintenance policy. Predictive replacement costs do include yard/quay and port call cost, as these costs are a direct result of the repair. However, storage costs are not included as scheduled maintenance provides an excellent opportunity for ordering the systems or components just in time, eliminating the requirement for storage.

2.3.3. 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 taken after a failure occurs; thus, the probability of failure is 100%.

The calculation of a proactive policy must include the failure probability. Including the failure probability, 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, before the scheduled maintenance.

A small calculation example: With a 10% failure probability, there is a 10% chance of a failure occurring before the scheduled maintenance, and there with a 90% chance that no failure occurs before the scheduled maintenance. 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 Failure < = > 90% chance 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 Eq.(3).

$$cost_{probability\ n} = \big((1-n) * \ cost_{proactive\ policy} \big) + (n * cost_{corrective\ policy}) \qquad (3)$$

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

Corrective Replacement Cost = €3000,-
Proactive Replacement Cost = €1500,-

((1-0.1) * €1500,-) + (0.1 * €3000,-)
(0.9 * €1500,-) + (0.1 * €3000,-)
$$Replacement\ Cost_{probability\ 0.1} = €1650,-$$

Thus, with Eq.(3) for both opportunistic and predictive maintenance, nine separate replacement costs are calculated. The time-to-failure and therewith the number of replacements of the corrective policy are assumed at the 90% failure rate, as explained. Calculating with this percentage, may lead to a relatively low number of replacements. This assumption is a simplification to obtain a first estimate. This concludes the replacement cost, moving to the off-hire cost calculation.

2.3.4. Off-hire Cost Calculation

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. Which means downtime of the system has a direct operational impact on the vessel. Off-hire cost 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 costs are based upon downtime [hours] of the vessel times the income/hour [€/hour] times the percentage of the cargo that the vessel cannot transport due to the downtime, as illustrated in Fig.6.

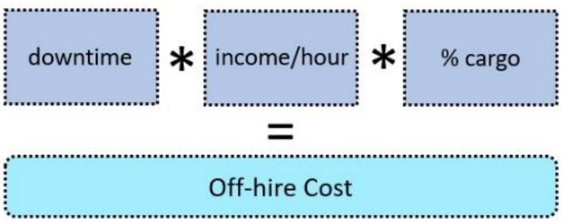

Fig.6: Abstract Representation Off-hire Cost Calculation

Downtime (in hours) is the time the vessel is not fully operational due to the failure.

Income/hour (€/hour) is the income per hour that is lost due to the failure

% cargo, some failures cause a vessel to carry less cargo (e.g. when a cargo cooling 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)

The off-hire cost calculation is the same for all policies. The difference in outcome between the policies comes from a difference in the length of downtime.

In a corrective policy, downtime is the repair time added to the delivery time of the system or the time the vessel takes to sail to the repair location. In opportunistic maintenance there is only downtime, when the repair time of a 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. Thus, in opportunistic maintenance the downtime is determined by a comparison of the time required for the class survey and the repair time only. In predictive maintenance, the downtime equals the repair time. When a repair is known in advance, the system can be ordered in time, eliminating delivery time.

The last aspect of the off-hire calculation is the calculation of the probabilities, as explained in section 2.3.2. For both opportunistic and predictive maintenance policies, nine different off-hire costs are calculated, based on Eq.(3). This concludes the off-hire cost calculation, next, the reputation cost calculation is explained.

2.3.5. 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, loss of reputation, loss of hire, loss of a long-term time-charter and even rejection from an oil major are risks of unforeseen maintenance. The difference between long term reputation damage and short-term reputation costs is already explained. As also that only short-term reputation costs are included in the MCM. Short-term reputation costs are the reputation costs directly induced by a failure on that vessel.

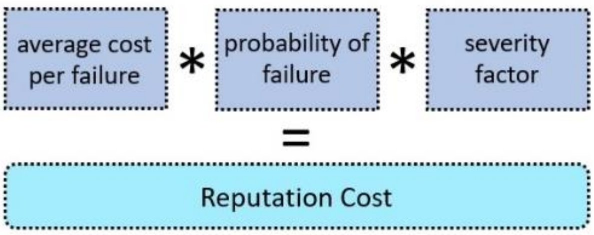

Fig.7: Abstract Representation Reputation Cost Calculation

In the reputation cost calculation, the average cost per failure is multiplied with the probability this failure occurs and a severity factor. Fig.7 shows a representation of the reputation cost calculation.

The probability of a failure has been discussed in section 2.3.1. The average cost per failure is quantified based upon company-specific historic data. The severity factor varies between 0 and 1. It 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.

2.3.6. Total Cost Calculation

Now, the total cost per policy can be determined. The sum of the replacement cost, off-hire cost, and reputation cost per failure results in the total cost per failure, as illustrated in Fig.8.

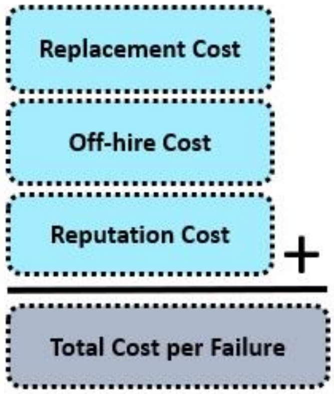

Fig.8: Total Cost per Failure

These total costs per failure have to be multiplied with the amount of failures. The final part of the calculation is determining the amount of failures (and their moment in time) over the remaining lifetime of a vessel.

The calculated MTTF combined with the downtime, results in a meantime-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 Eq.(4). With the amount of replacements determined, the amount of replacement times the total cost per failure, results in the total maintenance cost of that system over the lifetime of the vessel (see Eq.(5)).

$$Number\ of\ Replacement = \frac{Remaining\ Lifetime\ of\ Vessel}{MTBF} \tag{4}$$

$$Total\ Cost = Number\ of\ Replacement * Total\ Cost\ per\ Failure \tag{5}$$

Finally, these total costs are corrected, calculating the current value of future cost. For this calculation the company-specific weighted average cost of capital (WACC) and the inflation rate are utilised. This calculation is presented in Eq.(6).

$$Present\ Value\ Total\ Cost = \frac{Total\ Cost * Inflation\ Rate^{years}}{WACC^{years}} \tag{6}$$

When calculating the total cost of opportunistic and predictive maintenance policies, the complete set of failure probabilities is utilised. A comparison of the cost belonging to the different probabilities performed to find the optimal (lowest cost) maintenance policy. Therewith determining, the optimal coinciding failure rate, and the best time-to-failure. Therewith the MTTF, corrective, opportunistic and predictive maintenance calculations have been completed. The only part that remains is to compare these total costs and determine the optimal policy.

2.3.7. Comparison of Total Cost per Maintenance Policy

The result of the previous calculations is four total cost figures, two for corrective, one for opportunistic and one for preventive. The last part of the MCM is to compare and rank the four calculated total cost figures, from lowest to highest. Lower costs are desirable for any commercial company. This ranking, showing the four policies, as illustrated in Table II, is output of the MCM.

Table II: Maintenance Policies Ranking - Example

Policy	Cost
Opportunistic Maintenance	€ 200.000,-
Predictive Maintenance	€ 400.000,-
Corrective Maintenance – *o.o.b.d.*	€ 600.000,-
Corrective maintenance – *s.1.s.*	€ 800.000,-

Based on the ranking of the four maintenance policies, shipping companies can make a better-substantiated maintenance policy decision per individual system or component, based on the total cost per policy. Concluding with an overview of the entire model, in Fig.9.

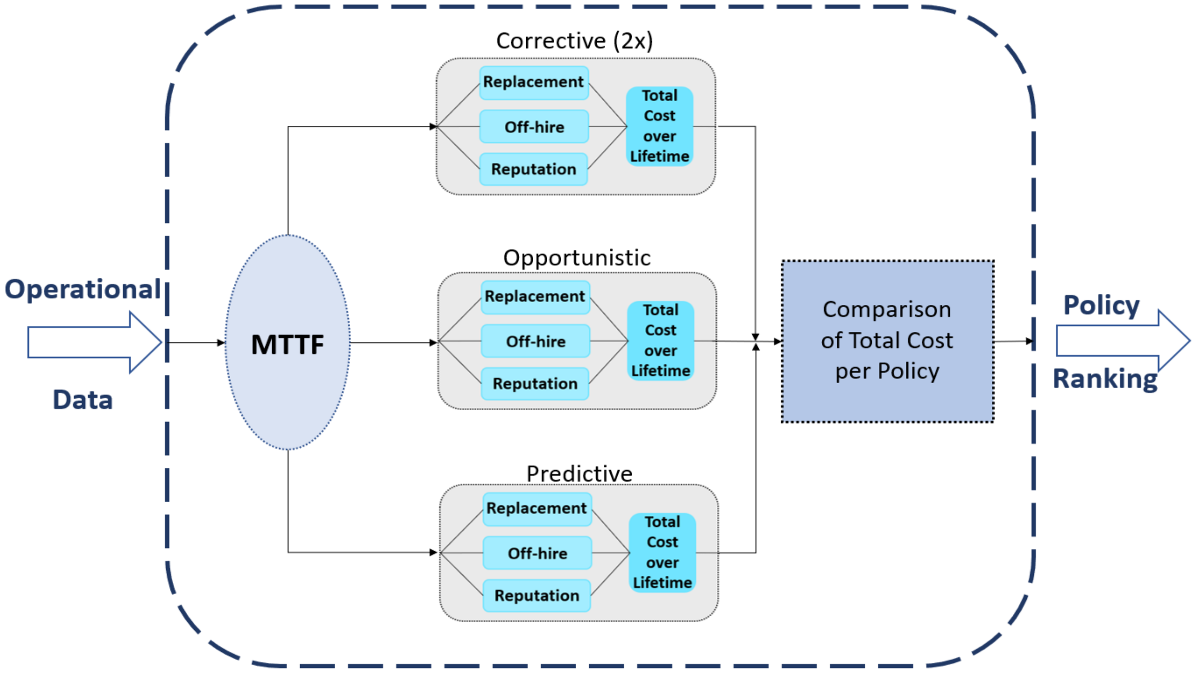

Fig.9: Overview Maintenance Cost Model

3. Case Study: Anthony Veder

3.1. Systems Used for Validation

The MCM is applied to calculate the maintenance cost for systems on board gas tankers of Anthony Veder. In this case study, systems are divided into balanced test-groups, representing systems onboard. The division is made based on system price, operational effect and mechanical or electric, Table III. In collaboration with maintenance experts of Anthony Veder, a system belonging in each group is selected.

Table III: Group Division

Group #	Electric	Mechanical	Effect on Operation	No Effect on Operation	Price < €5000,-	Price > €5000,-
Group 1	•		•		•	
Group 2	•		•			•
Group 3	•			•		•
Group 4	•			•	•	
Group 5		•	•			•
Group 6		•	•		•	
Group 7		•		•	•	
Group 8		•		•		•

3.2. Results Case Study

The failure behaviour is calculated based on the historic data from BASSnet, the vessel 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. The operational area is Europe and the delivery and storage location of the system are set in Rotterdam. All this input can be varied, in next applications of the MCM, however for the comparison in this case study only system specific variations are made.

Table 4 gives the outcome of the application of the MCM is presented and the recommended policy and corresponding financial improvement. This financial improvement is based on comparing the recommended policy with the policy currently applied by Anthony Veder. When the recommended policy is the currently applied policy, there is no cost improvement, shown with n/a.

Table IV: Maintenance Policy Comparison

Group #	Recommended Policy	Cost Improvement %
Group 1	Predictive	1%
Group 2	Proactive	0%
Group 3	Predictive	3%
Group 4	Corrective – o.o.b.d.	n/a
Group 5	Corrective – s.1.s.	70%
Group 6	Predictive	49%
Group 7	Corrective – o.o.b.d.	n/a
Group 8	Corrective – o.o.b.d.	n/a

When evaluating the recommended policies and the improvement percentage. In four groups the recommended policy leads to a cost improvement. The impact per system may vary between 0 and 70%. The average improvement over the 8 groups is, 16%. This is per component on board, so using the MCM to substantiate the maintenance policy for all systems on board, all vessels of a fleet, could lead to a substantial financial benefit. Based on the results of group 5 and 6, it seems that for mechanical systems that influence the operation, cost savings of 60% on average are possible. However, further investigation is required to further validate this claim.

In group 1-3 it can be seen there is (almost) 0% cost improvement. This means that the recommended policy is different from the currently applied policy, but does not lead to cost reduction. Apart from cost reductions there are several other reasons why another policy can be beneficial. For instance, reliability, maintenance frequency or a different level of uncertainties. In this particular case it has been determined that a proactive policy is an improvement compared to the currently applied policy, despite the lack of cost reductions. This illustrates the MCM is not developed to make a decision, only to help substantiate the decision-making process.

4. Discussion of Results

4.1. Novel Approach

This research opens the door for a new way of estimating maintenance cost in shipping. It breaks with the current manner in which the operational costs of a vessel are estimated based on scheduled maintenance jobs, it does not include unforeseen repairs. This novel approach concerns the costs of corrective, opportunistic and predictive maintenance, based on system specific failure data. The model generates a, system specific cost-based ranking of these maintenance policies. The ranking can be used by ship management companies, to obtain a better substantiated system specific maintenance policy.

4.2. Model Usability

The model is suited for all components, systems and engines of a vessel. Depending on the Planned Maintenance System a company uses, the failure behaviour can be calculated real-time. The calculations are based on system-specific and company-specific variables. The company-specific variables can be adjusted once, in first application of the model. Concluding, the developed model is usable for different systems and companies.

4.3. Validity

During the research there were several assumptions and limitations to the developed model. This paragraph will highlight the most critical points of discussion with regards to the assumptions and limitations.

- 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.
- The time-to-failure and therewith the number of replacements of the corrective policy are assumed at the 90% failure rate. Calculating with this high percentage, leads to a relatively low number of replacements. As it is likely there are more replacements, it is likely that systems break down earlier. This means 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.
- The 60% improvement shown in the results of the mechanical equipment emphasizes the validity of the 90% failure probability assumption. 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, the boundaries of the different cases can be established.

5. Conclusion

The goal of this research is to present a way to improve the maintenance cost calculation of ship management companies, especially for those with a profit objective. The Maintenance Cost Model is presented and integrates actual operational data from a vessel in the maintenance cost estimation. The operational data from vessels is used to determine the failure behaviour of the systems on board. 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, which can be used by ship management companies, to obtain a better-substantiated system-specific maintenance policy.

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 ship management company this is important information, that ensures improved true operating costs due to an adapted maintenance approach. The developed model in this research is generally applicable and proves the concept.

Next to these improved operating 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.

Recommendations for further research comprise the expansion of the Maintenance Cost Model by means of; increasing the likelihood of replacements, including business cycle predictions, expanding from one vessel to a fleet and including other maintenance policies.

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